Development Lines of Improved Physical Modeling at DLR

Window on Science Seminar

24 September 2018

US Air Force Research Laboratory (AFRL)
Wright-Patterson Air Force Base, OH, USA

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DLR, Institute for Aerodynamic and Flow Technology
$C^2A^2S^2E$, Turbulence & Transition Group

C²A²S²E

Center for Computer Applications in AeroSpace Science and Engineering

DLR

The German Aerospace Center - DLR

- Three primary functions
  - National aeronautics and space research center of the Federal Republic of Germany
  - Germany's space agency
  - One (out of a number of) project management agencies for national research projects

The German Aerospace Center - DLR

- Three primary functions
  - National aeronautics and space research center of the Federal Republic of Germany
    - Personnel: ~ 6000
  - Germany's space agency
    - Personnel: ~ 800
  - One (out of a number of) project management agencies for national research projects
    - Personnel: ~ 1200

The German Aerospace Center - DLR

headquarters

- 6 research areas:
  - **Aeronautics**
  - Space
  - Energy
  - Transport
  - Digitalisation ***(new)***
  - Security ***(new)***

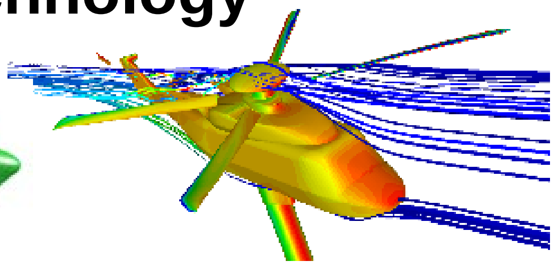
Braunschweig: H. Blenk, A. Busemann, …

Institute for Aerodynamic and Flow Technology

Göttingen: L. Prandtl, H. Schlichting, W. Tollmien, Th. von Kármán, …

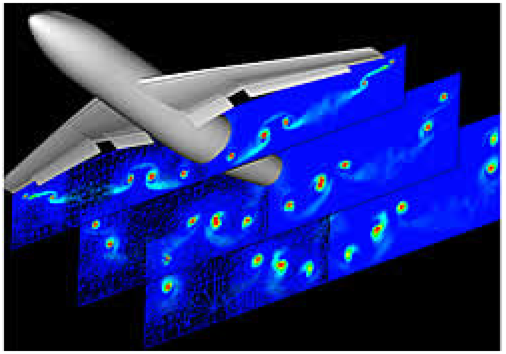
- 8100 employees in 40 institutes at 20 sites in Germany

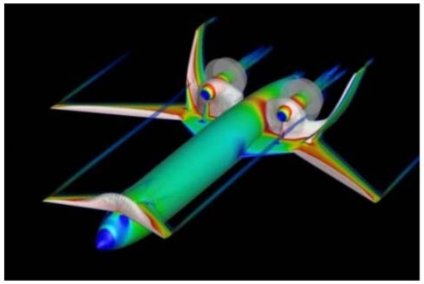
Institute for Aerodynamic and Flow Technology

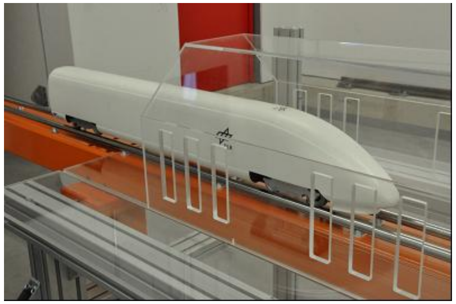


Research and work areas

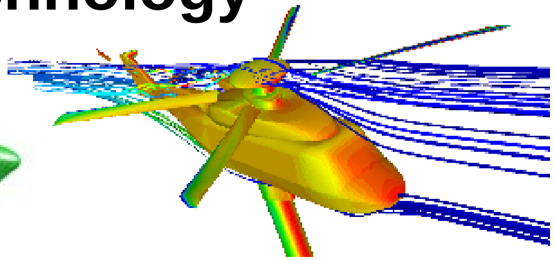
- Software Development
- Aircraft Aerodynamics
- Aircraft Design and Assessment
- Experimental Methods
- Military Aircraft
- Helicopter Aerodynamics
- High-Speed-Configurations
- Spacecraft
- Aeroacoustics
- Technical Flows
- Flow Measurement Technology
- Acoustic Measurement Technology
- Hardware







Institute for Aerodynamic and Flow Technology



- **Research and work areas**
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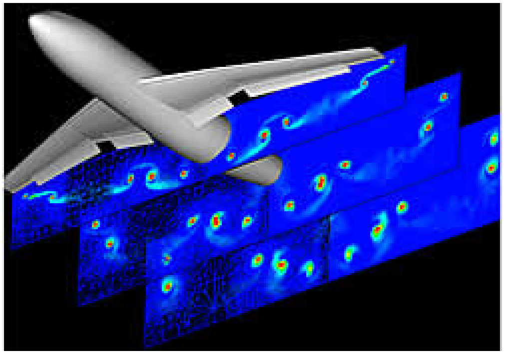
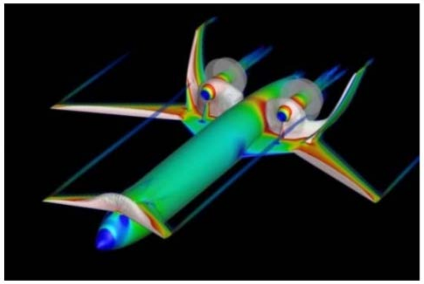
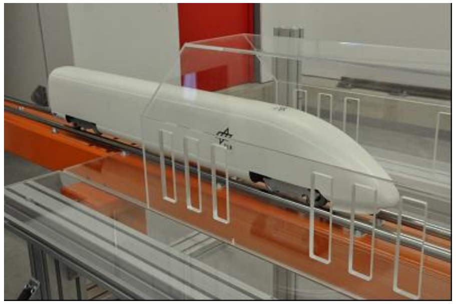






Outline

- Introduction
- Reynolds stress models (RSM)
- Scale resolving simulations (SRS)
- Transition prediction and modeling
- Turbulence modeling improvements
- Outlook

Introduction

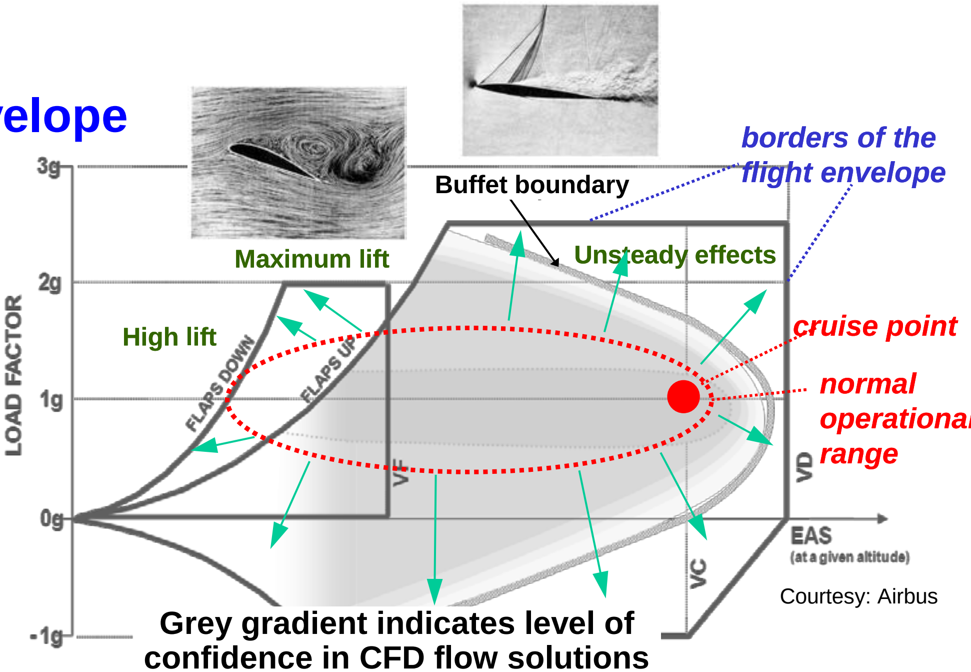
Overview

- $C^2A^2S^2E$ – Numerical Methods Branch → CFD Code Development
  - **TAU code** – external aerodynamics, unstructered, FV, compressible
    → air vehicles
  - **THETA code** – internal/external flows, unstructered, FV, incompressible
    → combustion, wind turbines, two-phase flows (gas/liquid)
  - ***Flucs*** (FLexible Unstructured CFD Software) – external aerodynamics
    → DLR's 'next generation' flow solver
    → unstructured, 2nd order FV branch + HO-DG-branch, compressible/incompressible
    → massive hybrid parallelization
    → flow-solver component of a multi-disciplinary simulation system FlowSimulator
    → development currently ongoing
    → 1st release planned for 12/2021
- Main Customers
  - *Internal:* Transport Aircraft, Helicopters (incl. Wind Turbines), High-Speed Configurations, Spacecraft
  - *External:* Airbus Operations
- ***Focus:*** Transport Type Aircraft

Our major driver: *The Digital Aircraft*

Numerical Analysis of Full Flight Envelope

- **Extension** of **confidence region** towards edge of flight envelope
  - Unsteady flows
  - Strong non-linearities
    - Separated flow regions
    - Strong shocks
    - Shock/boundary-layer interaction
    - …



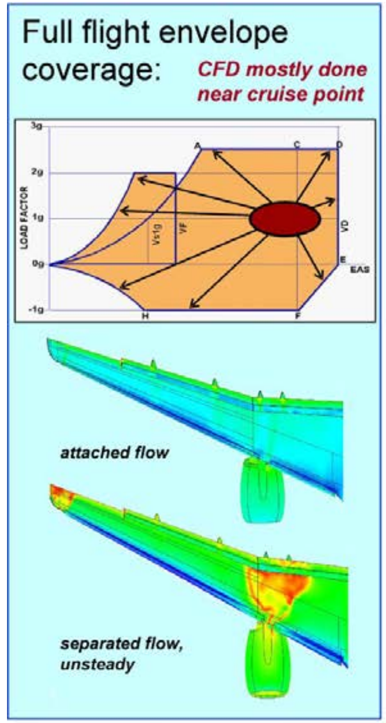
Courtesy: Airbus

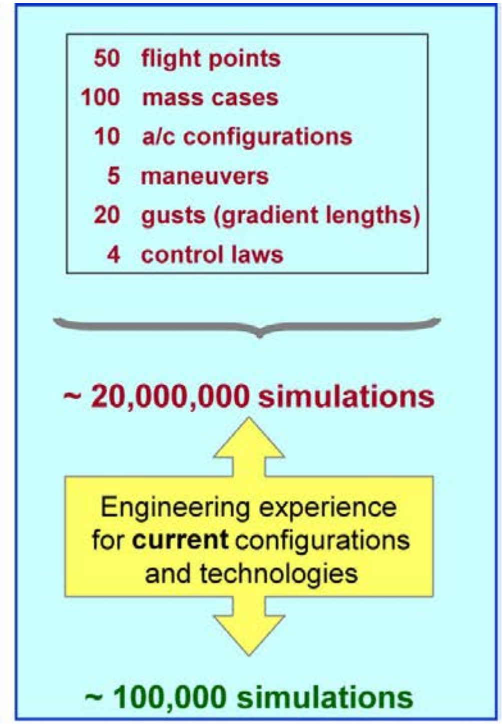
- CFD **solver capabilities growing**
    - Discretization schemes
    - Grid generation, higher resolution, geometrical complexity and details, …
    - HPC capacities and parallelization strategies
    - …
- **Turbulence** and **transition** models **have to keep up** with solver capabilities.
  - **Coupling** and **extension** of models needed.

Vision: The Digital Aircraft

Future goal for CFD

- Aircraft design and analysis based strongly on numerical simulation
- Bring down number of computations necessary and free from **current** configuration knowledge
- Two basic concepts



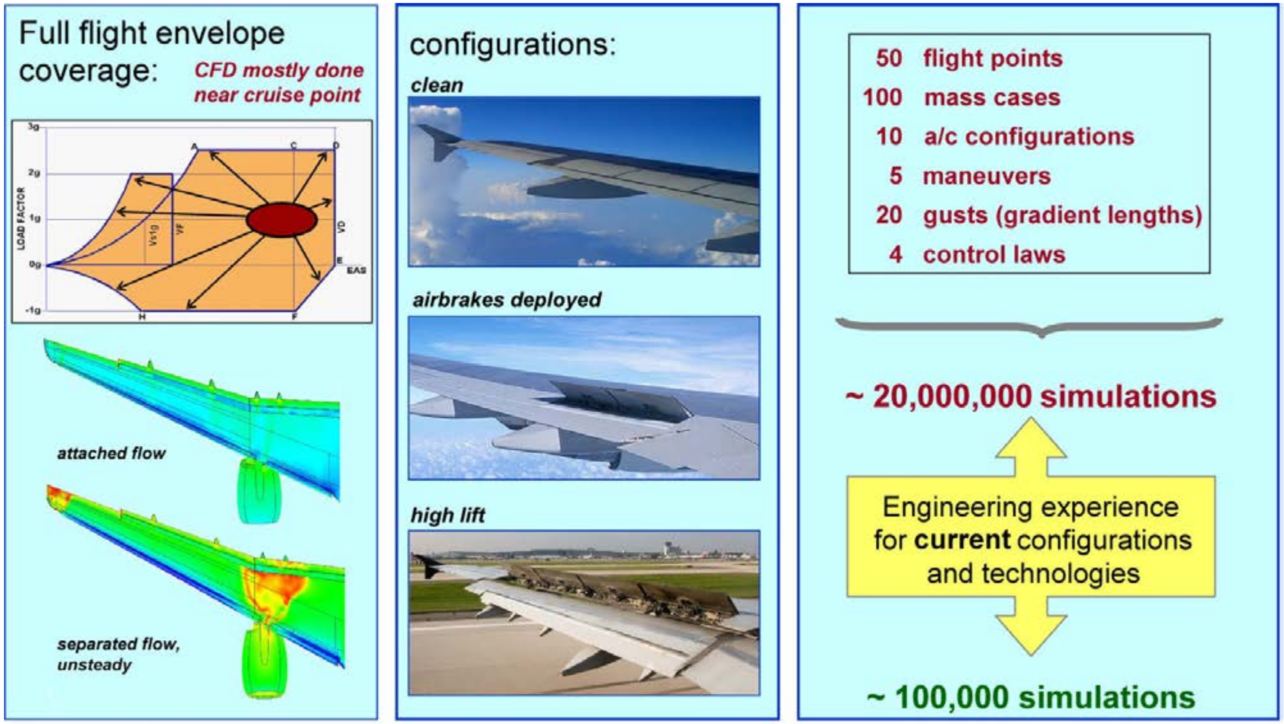


  - Time accurate maneuver simulations: ***Flying the equations***
  - Generation of aerodynamic/aeroelastic data: ***Flying through the data base***

Vision: The Digital Aircraft

Future goal for CFD

- Aircraft design and analysis based strongly on numerical simulation
- Bring down number of computations necessary and free from **current** configuration knowledge
- Two basic concepts
  - Time accurate maneuver simulations: ***Flying the equations***
    → **Physical Modeling for High Fidelity CFD**
  - Generation of aerodynamic/aeroelastic data: ***Flying through the data base***



Vision: The Digital Aircraft

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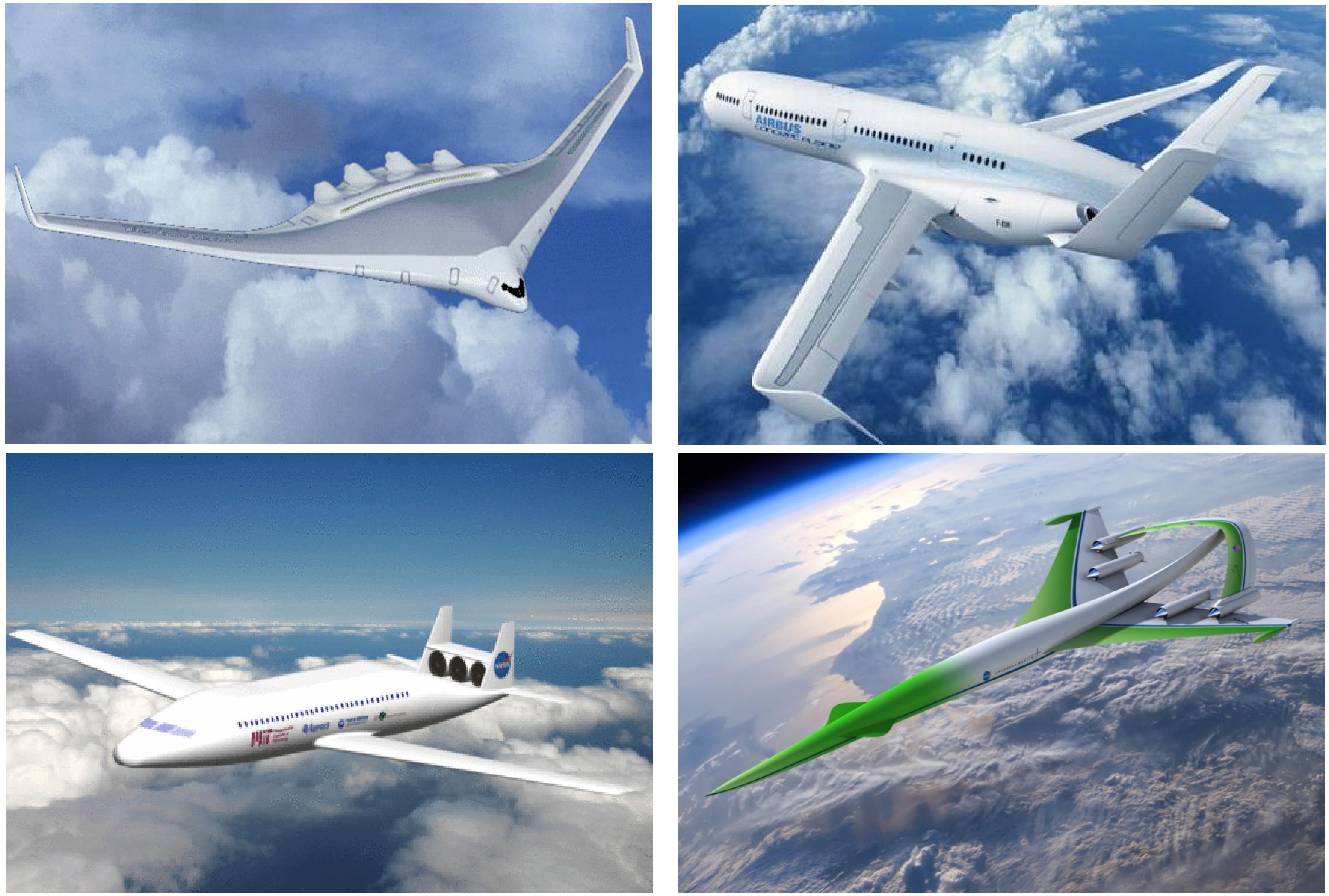
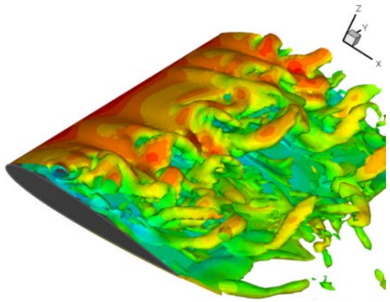
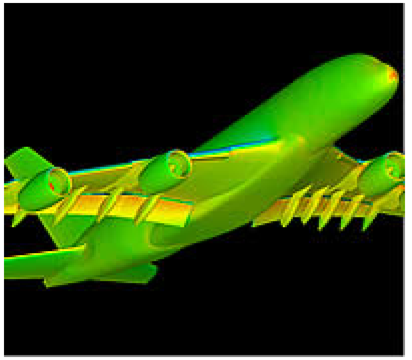
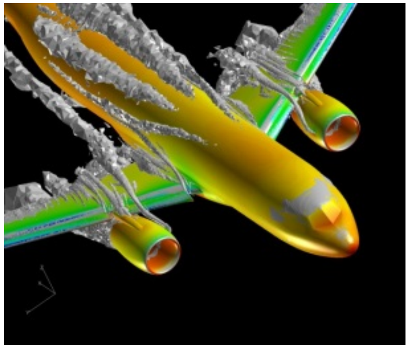
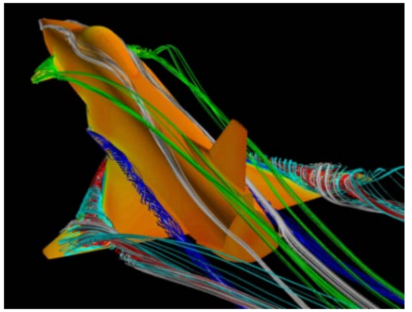


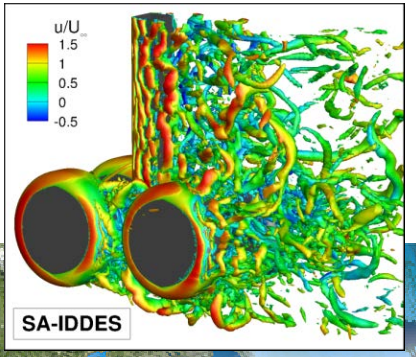
Vision: The Digital Aircraft











Numerical Analysis of Full Flight Envelope

- For accurate predictions, besides high grid resolution and accurate numerical handling of the equations **physical modeling** is a key issue.
- ***Four development lines***:
  1. Reynolds stress models (RSM)
     - As standard RANS approach for any kind of configuration (including highly complex industrial configurations)
  2. Scale resolving simulations (SRS)
     - Targeted application for specific components of aircraft or military configurations
  3. Transition prediction and modeling
     - Necessary condition for accurate results of turbulence models within the full flight envelope
  4. Turbulence modeling improvements
     - Targeted experimental (physical & numerical) investigations for specific flow phenomena

DLR

C²A²S²E

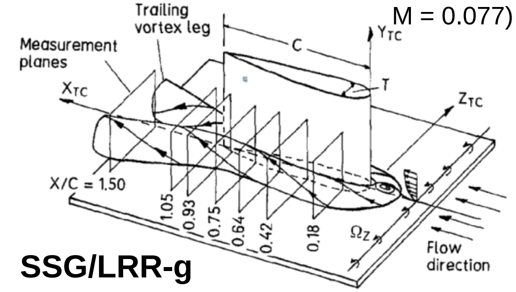
Reynolds stress models

Differential RSM (DRSM)

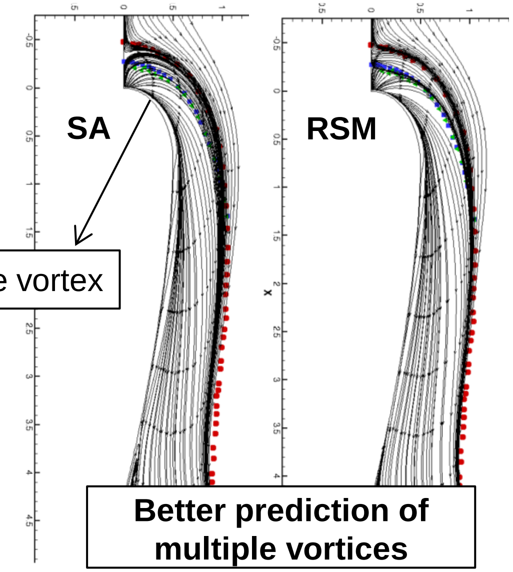
- DRSM represent highest level of RANS-modeling
  - Individual equations for stress components
    → Anisotropy of turbulence inherently accounted for
  - Effects of rotation and streamline curvature included
    → No corrections for free vortices necessary
  - No stagnation point anomaly
  - 7 model equations
- Sometimes lack of robustness for complex configurations
- DRSM in TAU
  - SSG/LRR-ω model (standard model)
    - Based on Menter's BSL ω-equation
  - Exact transformation to g = $1/\sqrt{\omega}$ and to $\tilde{\omega} = ln(\omega)$
    - Higher numerical stability + no near wall grid dependence
  - ε^h-JHh-v2 model (Jakirlic-Hanjalic + ISM of TU-BS)
    - Based on homogeneous dissipation rate ε^h
    - Advanced near-wall treatment + anisotropic dissipation

a breakthrough?

Simpson wing
Re = 1.3×10^6
M = 0.077)

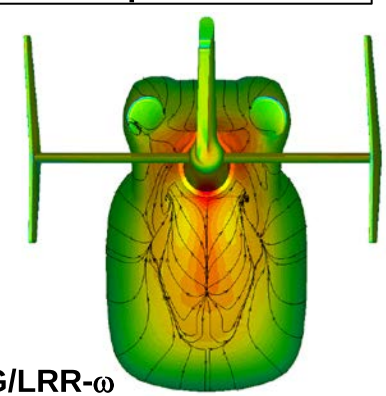


SSG/LRR-g

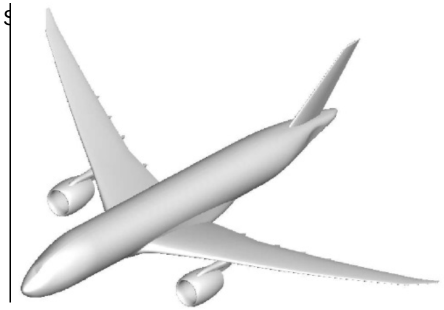


only one vortex

Better prediction of multiple vortices



SSG/LRR-ω

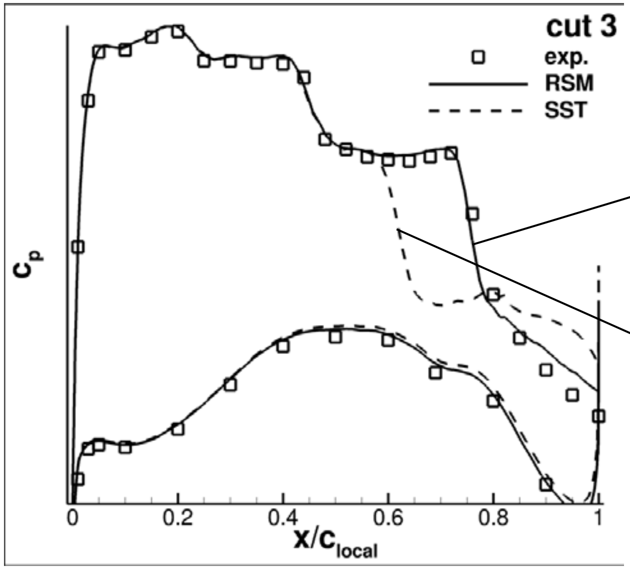


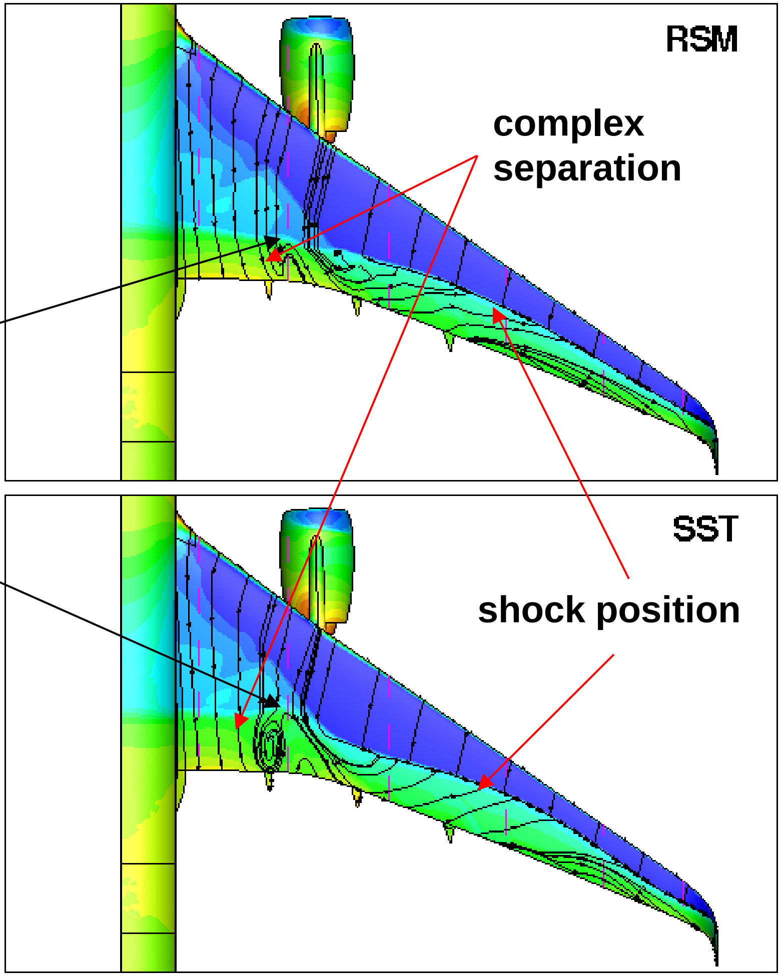
Reynolds stress models

Application of Reynolds Stress Models

Realistic aircraft configuration

Re = 40×10^6, M = 0.85, α = 2.0°





- Significant better shock prediction
- Very different separation pattern

Reynolds stress models

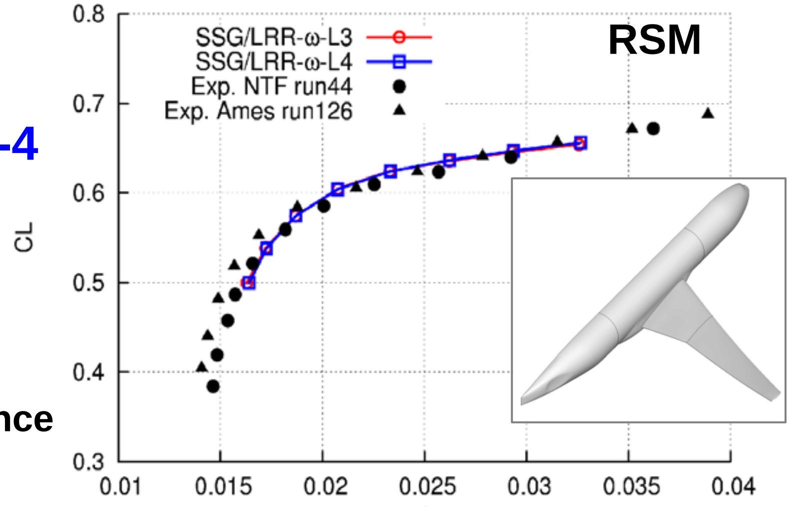
Application of Reynolds Stress Models

NASA Common Research Model (CRM), DWP-4

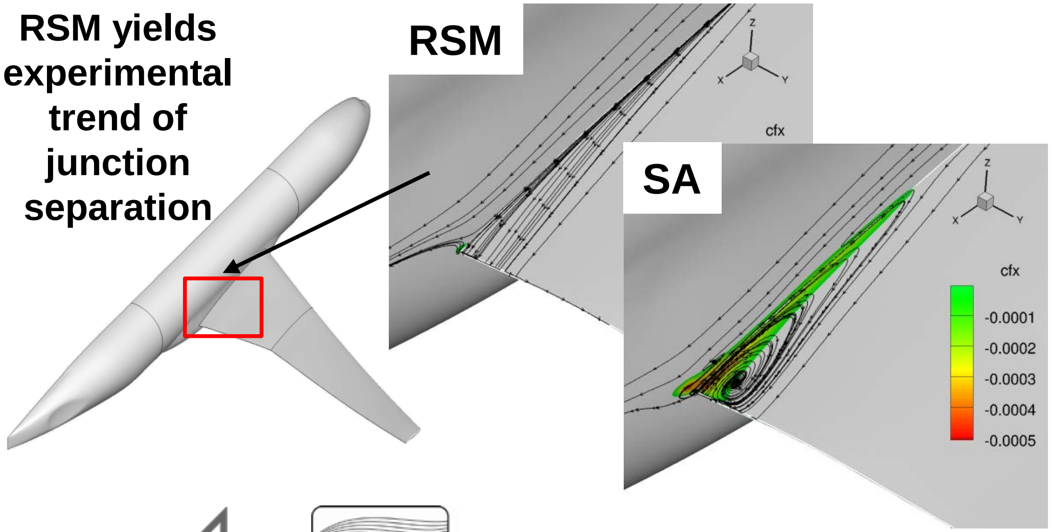
Re = 5×10^6, M = 0.85, α = 2.0, 2.75, …, 4.0

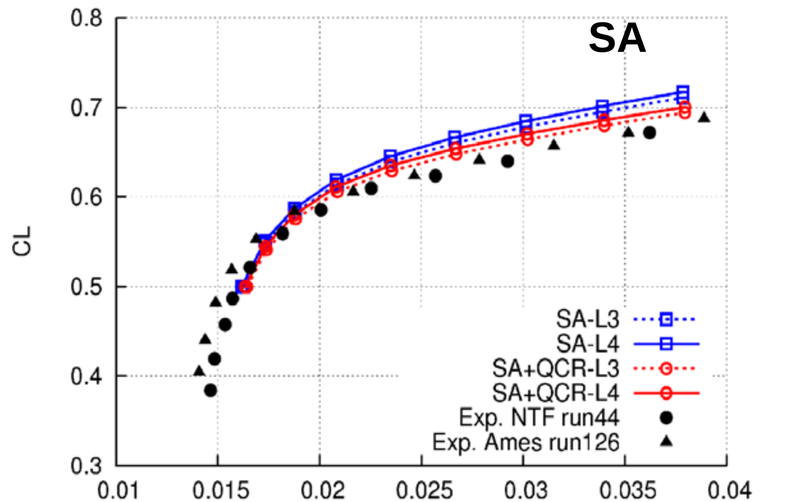
Grids: **L3(5M), L4(17M)**

RSM shows very low grid dependence



RSM yields experimental trend of junction separation



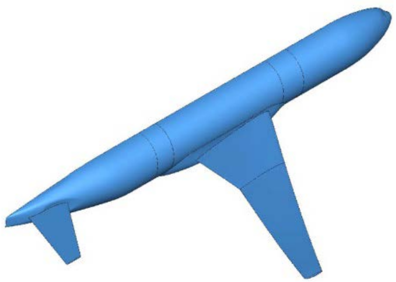


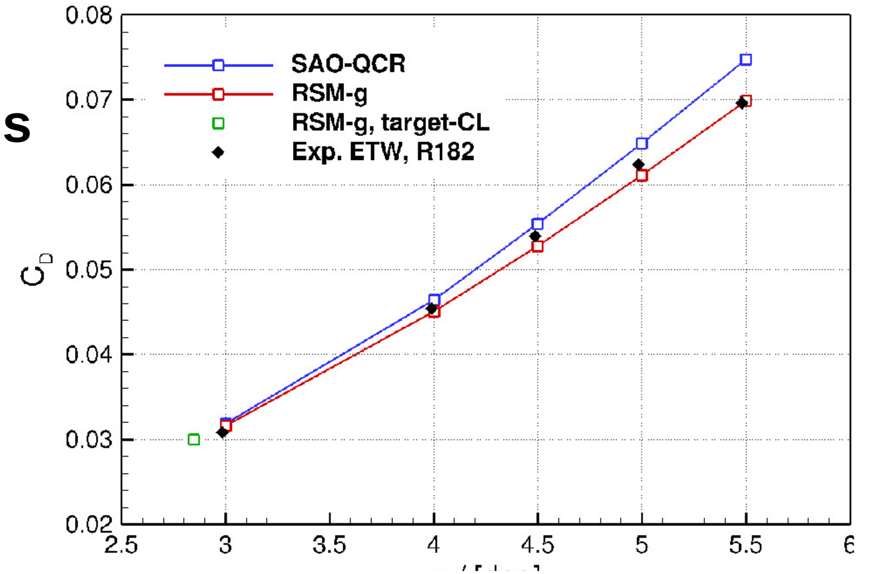
Idealized drag coefficient

Reynolds stress models

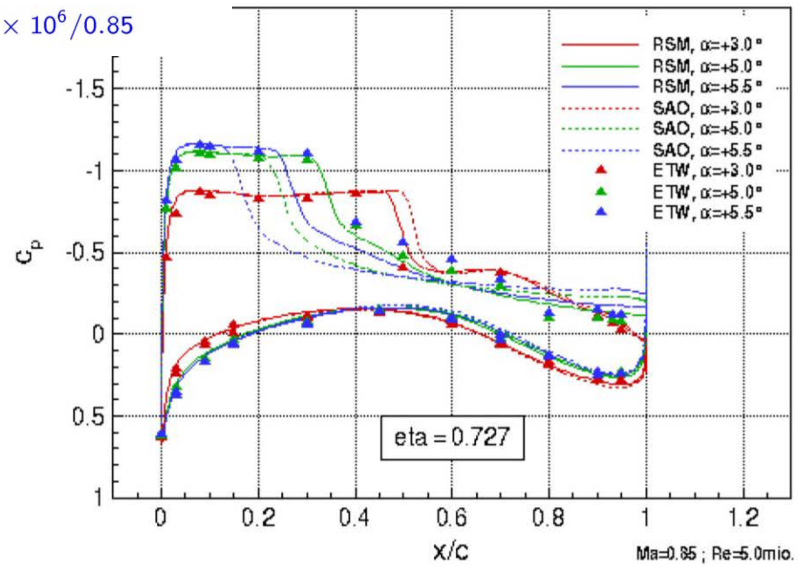
Application of Reynolds Stress Models

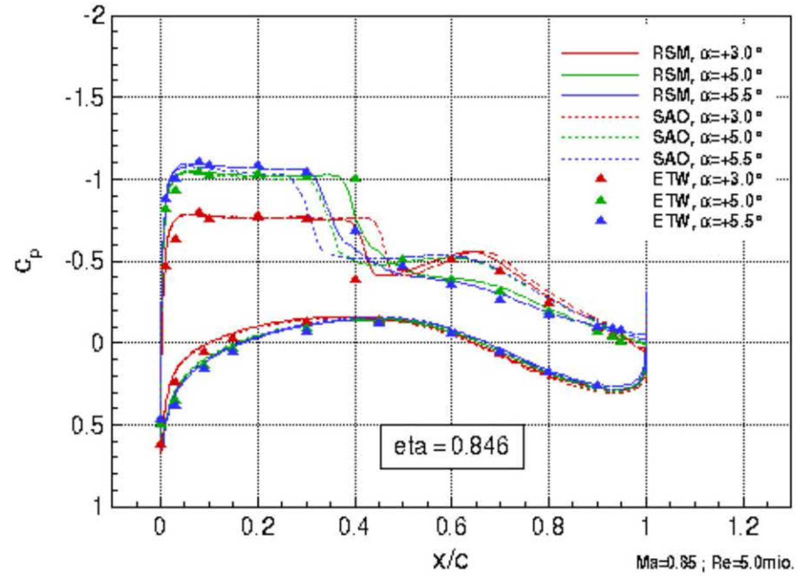
NASA Common Research Model (CRM)





$Re/Ma = 5 \times 10^6/0.85$





Results from: Stefan Keye and Ralf Rudnik. "Validation of Fluid-Structure Coupled Wing Deformation Simulations for the NASA Common Research Model". 5th *CEAS Air & Space Conference*, Delft, The Netherlands, 7-11 Sept 2015. Paper No. 103.

Source: PhD thesis A. Probst

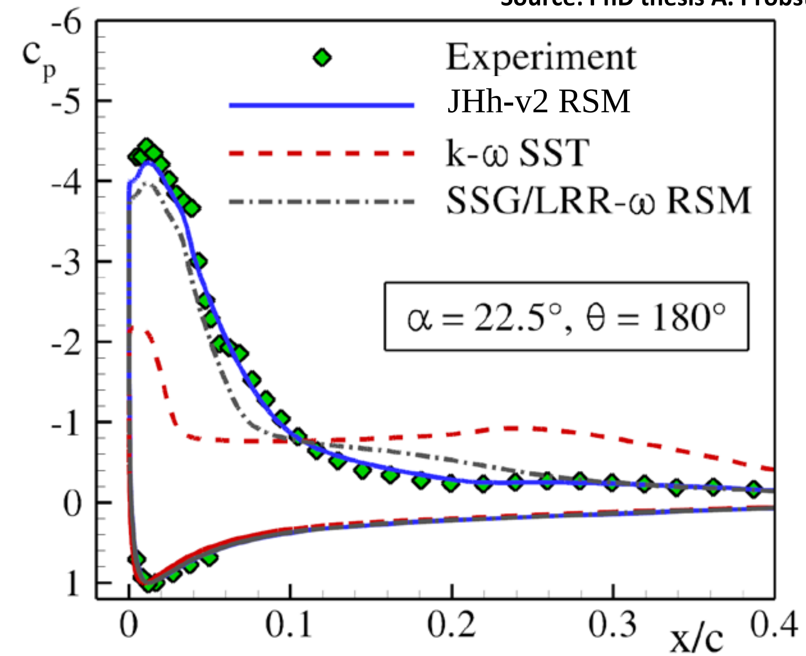
Reynolds stress models

Application of Reynolds Stress Models

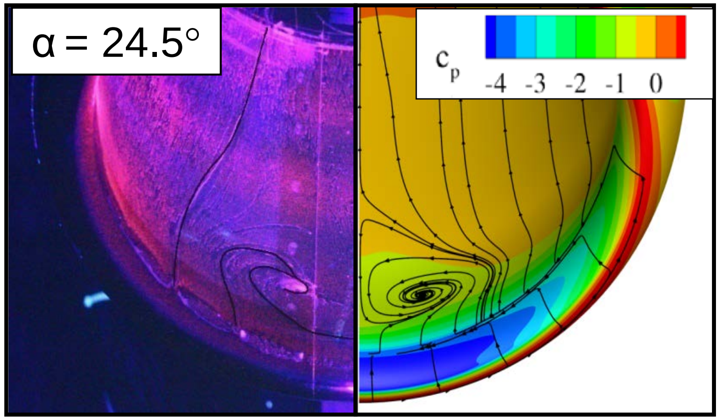
Flow-through nacelle at stall

Re = 1.3×10^6, M = 0.11

- URANS combined with e^N method
- Measured separation onset around $\alpha \geq 24°$
- Improvement by DRSM
- In particular ε^h-JHh-v2 model
  - Coefficients depend on turbulence quantities
  - Uses ε^h instead of ε: by targeted calibration matching with DNS data near walls achieved



Surface pressure in inlet symmetry plane

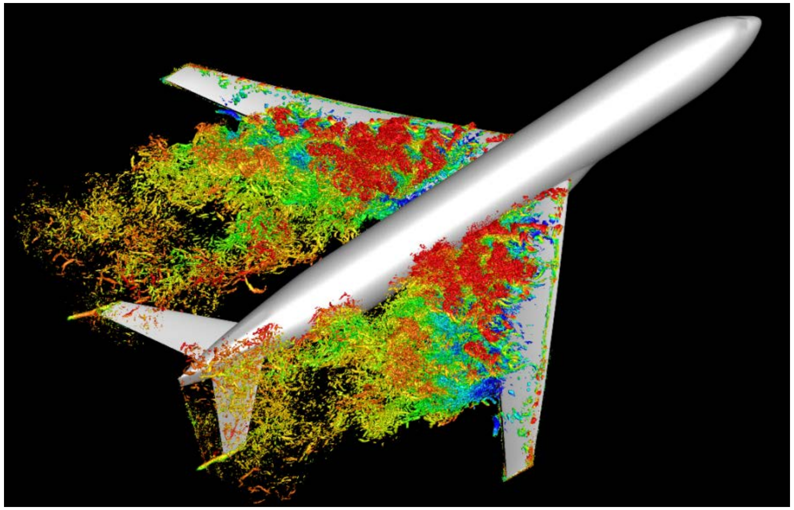


Oil-flow picture (left) and JHh-v2 RSM (right)

Scale resolving simulations

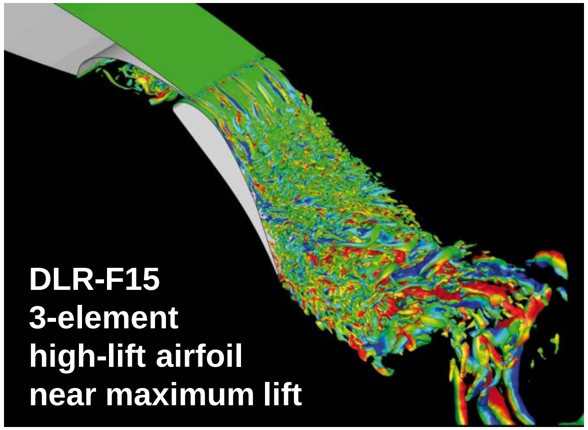
Basic approach

- Classical hybrid RANS/LES models
  - Detached-Eddy Simulation (DES, 1997)
  - Delayed DES (DDES, 2006)
  - Improved DDES (IDDES, 2008)
  - Coupled with SA or k-ω type RANS models



NASA CRM at low speed and high AoA

- Numerics
  - 2^{nd} order central spatial discretization of all equations
  - 4^{th} order matrix artificial dissipation with $k^{(4)} = 1/128$
  - Skew-symmetric convective fluxes (for kinetic energy conservation)
  - Low Mach number preconditioning (LMP) for $M < 0.3$
  - 2^{nd} order dual-time stepping
- Range of applicability
  - Flows with **massive** local **separations**
  - Clear **distinction** between **attached** (stable) and **separated** (unstable) regions

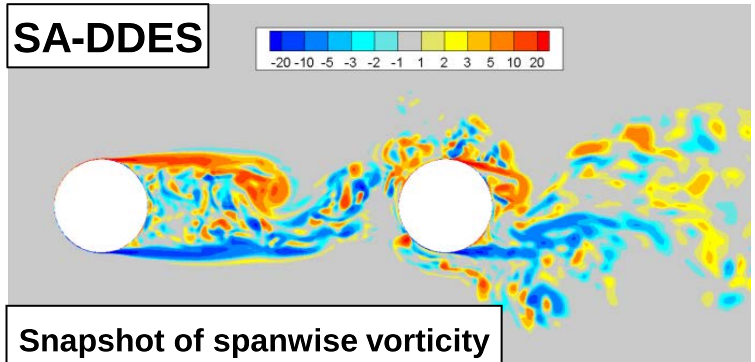


DLR-F15 3-element high-lift airfoil near maximum lift

Scale resolving simulations

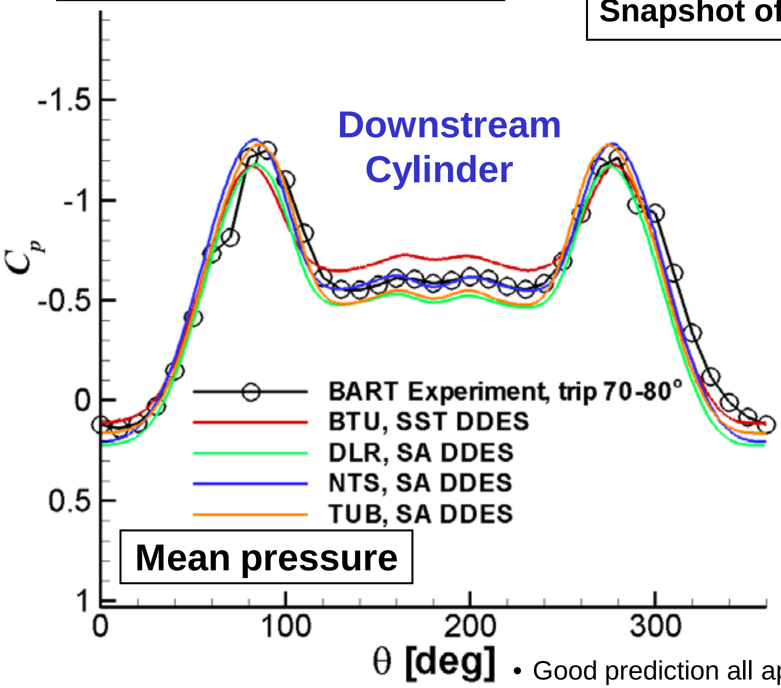
Sample applications of basic approach

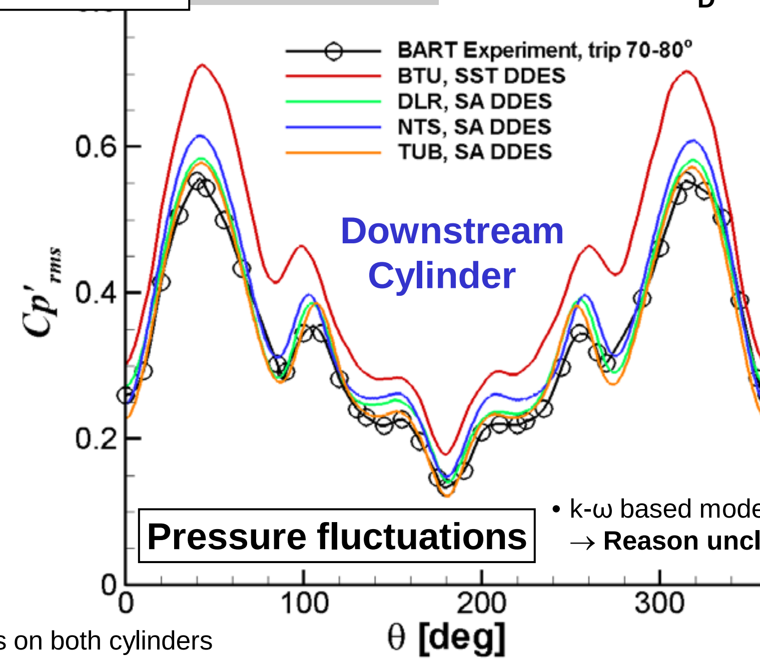
NASA tandem cylinder



- L/D = 3.7
- M = 0.1285
- $Re_D = 1.66 \times 10^5$

TAU results: green



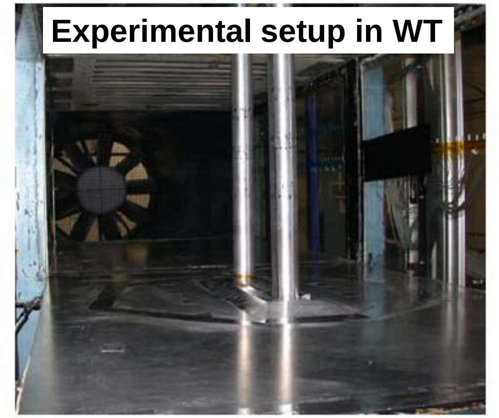


- k-ω based models too “noisy”
  → **Reason unclear**

- Good prediction all approaches on both cylinders
- Influence of numerical method and underlying RANS model small

Scale resolving simulations

Sample applications of basic approach



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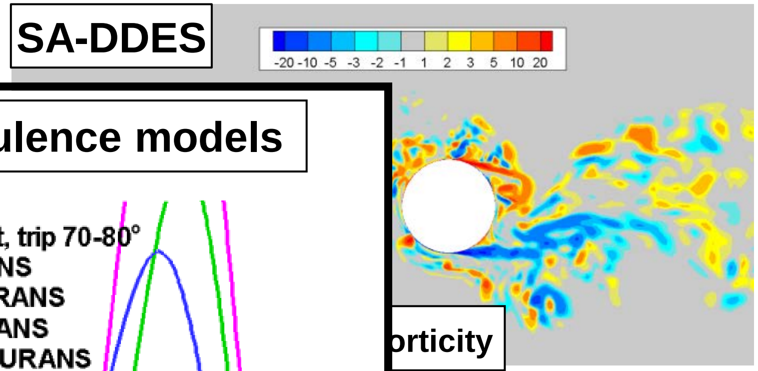

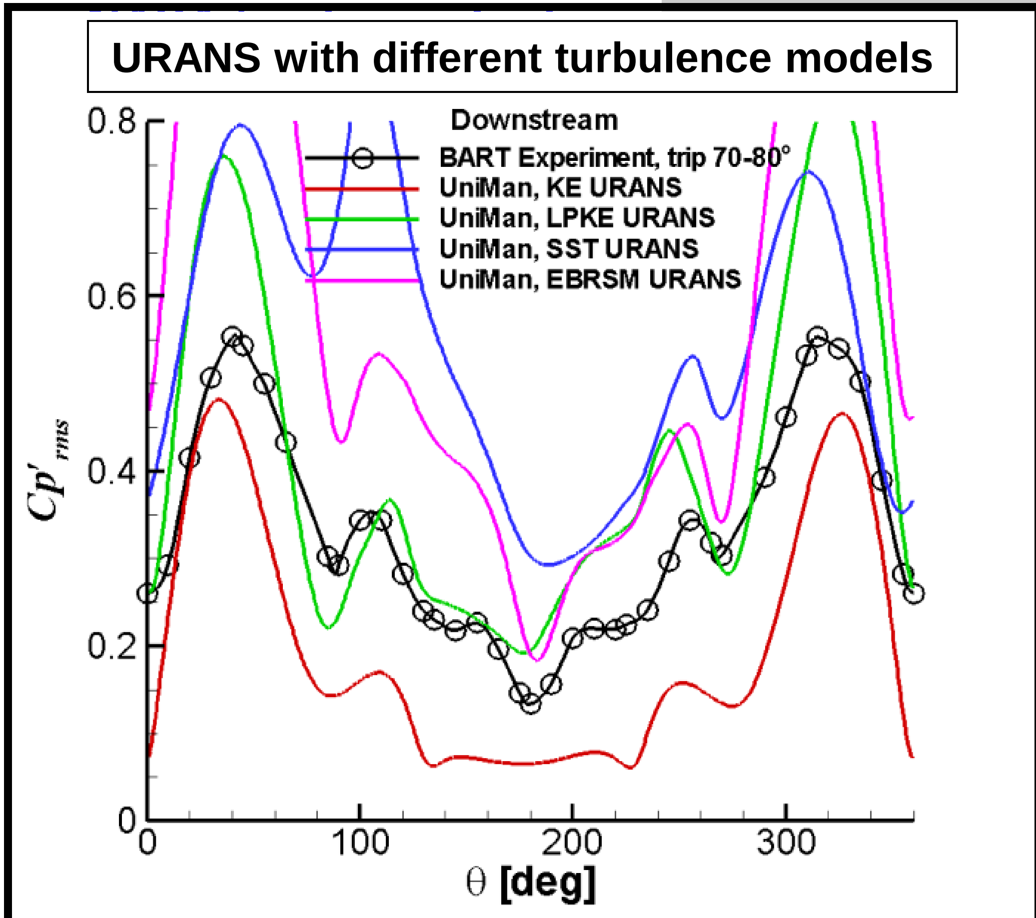

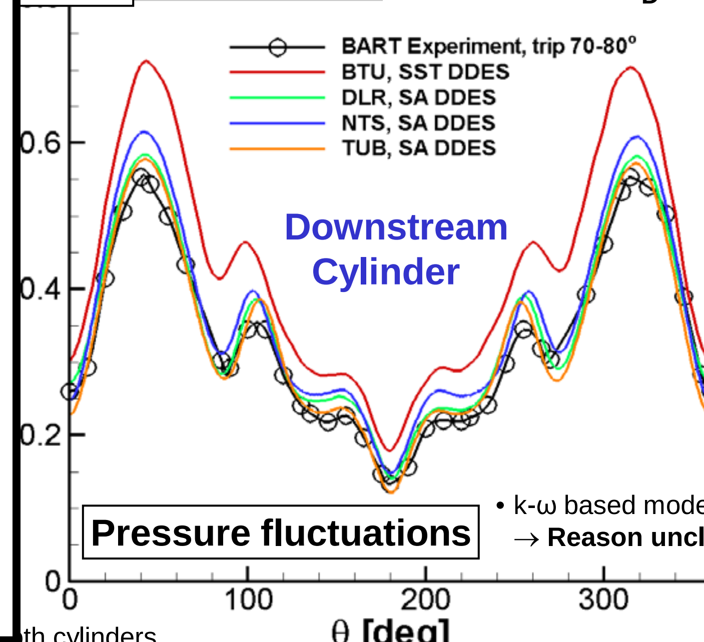

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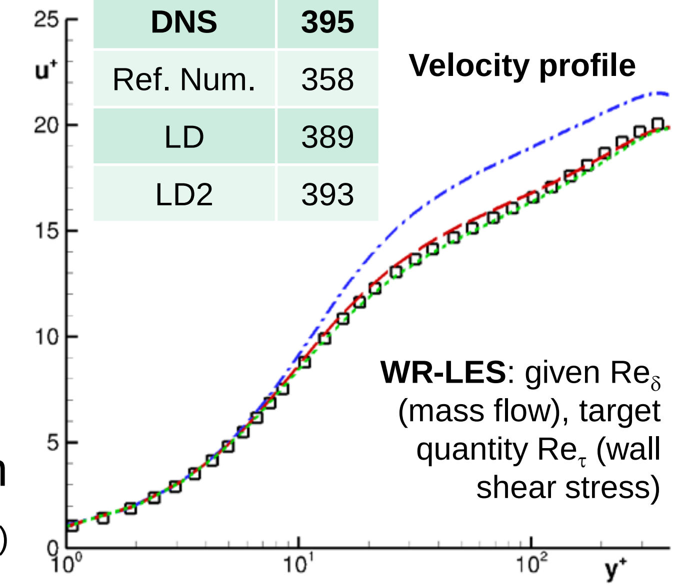
LES

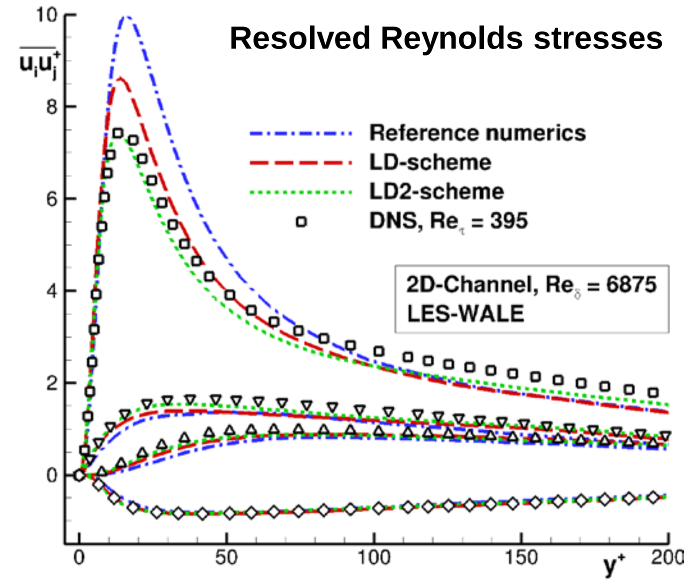
Scale resolving simulations

Extended approach

- **Improved Numerics**
  - Better satisfying general LES requirements
    $\rightarrow$ Very high accuracy $\rightarrow$ low dissipation (LD) and low dispersion (LD2)
    - **LD2-scheme**: 2nd-order central scheme with
      - **Reduced dissipation** settings (optimized)
      - **Reduced dispersion** by appropriate flux reconstruction
  - Test with pure LES applications, e.g. **periodic 2D channel flow**
  - Switch of standard RANS scheme into LD2 scheme for LES: **apply optimized numerics in LES regions only**
    $\rightarrow$ Adaptive numerical scheme for hybrid RANS/LES computations

	Re_τ
DNS	**395**
Ref. Num.	358
LD	389
LD2	393





DDES

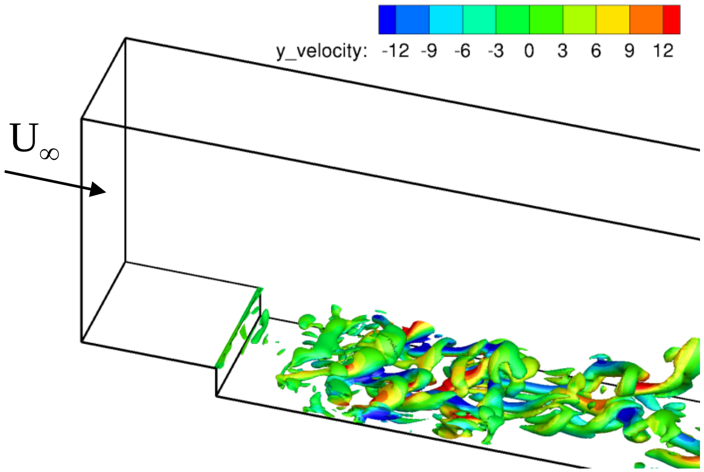
Scale resolving simulations

Sample applications of extended approach

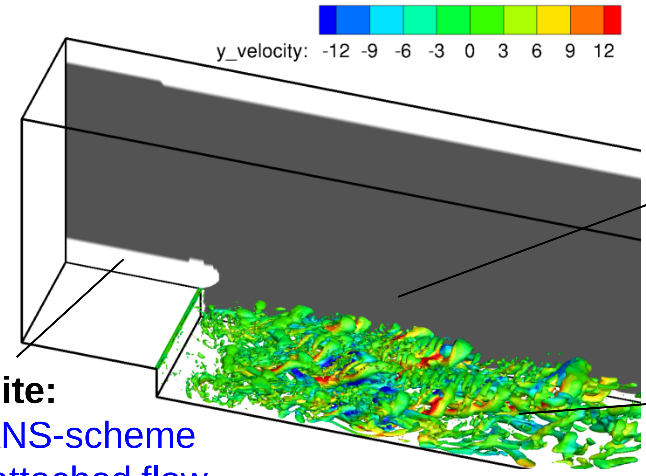
Flow separation at backward facing step (BFS)

- SA-DDES of backward-facing step; Re_h = 38,000
- **Optimized scheme in LES region, standard stable scheme in RANS region**
- Switch based on **suitable sensor function** (l_{hyb}/l_{RANS} sensor)

Standard scheme



Optimized scheme: adaptive RANS/LES numerics



grey:
Optimized LES-scheme in separated/re-attachment region

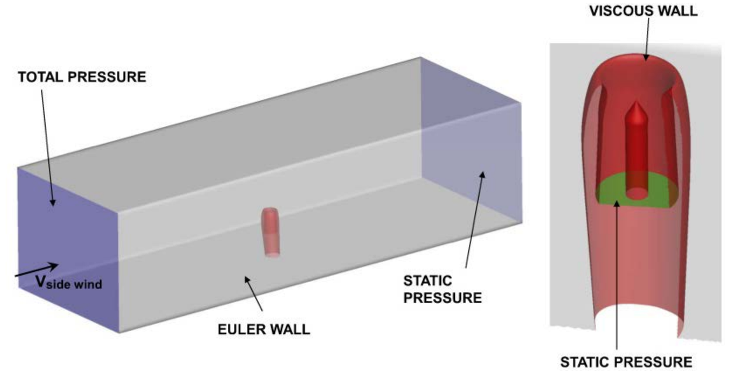
white:
RANS-scheme in attached flow

Improved resolution in LES region (Q-criterion)

IDDES

Scale resolving simulations

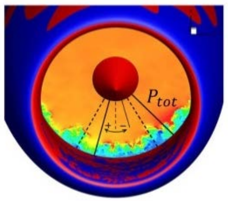
Sample applications of extended approach

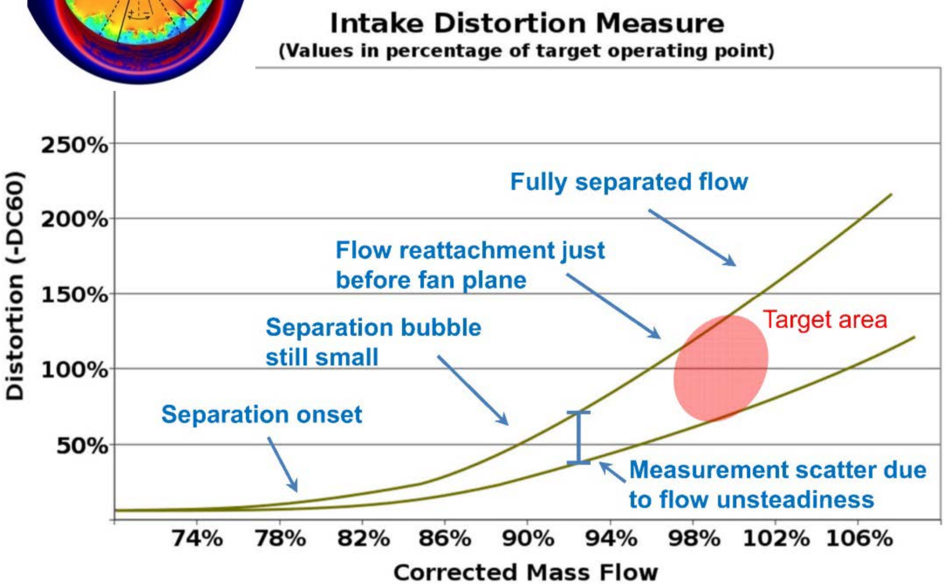


Aircraft nacelle in side wind (1)

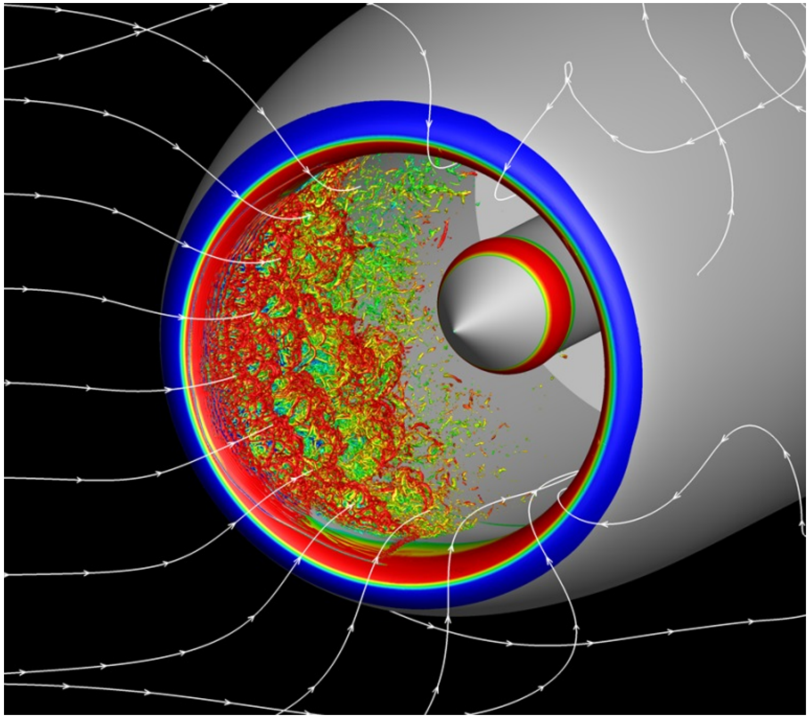
- SST-IDDES + adaptive scheme with LD2

$$DC60 = \frac{P_{tot}(60°) - P_{tot}(360°)}{q_\infty}$$





X



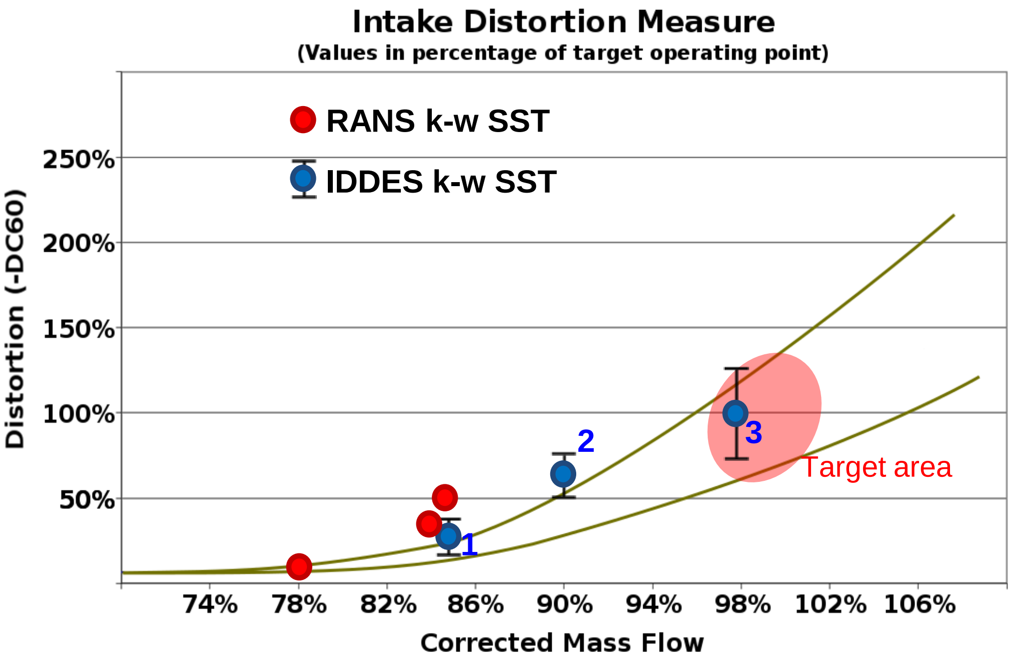
IDDES

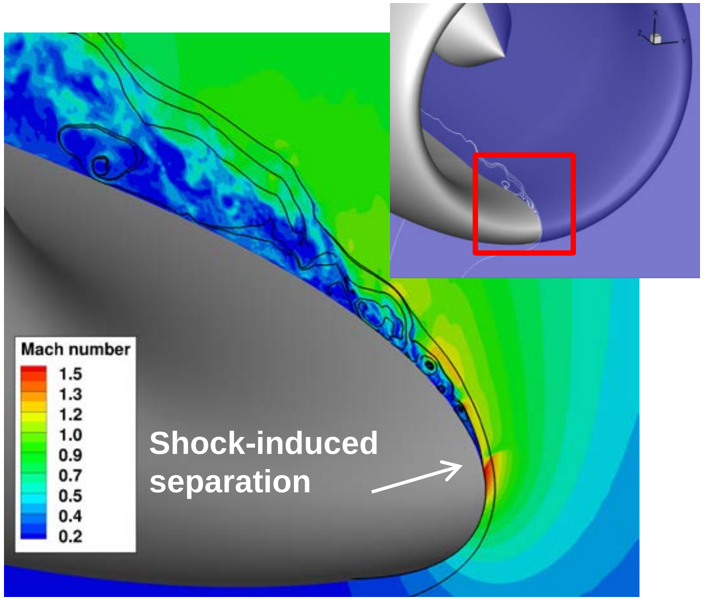
Scale resolving simulations

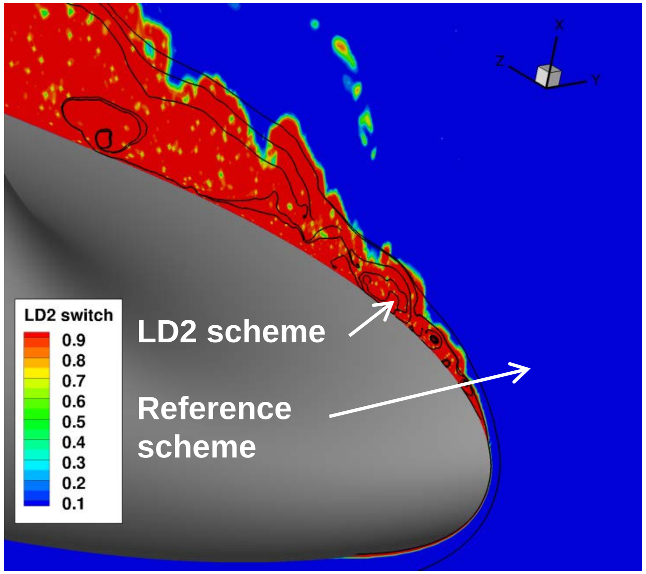
Sample applications of extended approach

Aircraft nacelle in side wind (2)

- SST-IDDES + adaptive scheme with LD2







Scale resolving simulations

Extended approach

- **Improved Modeling** → *Towards extension of the applicability range* *<u>from massive</u> to <u>incipient separation</u>*
  - **Three areas**
    1. RANS/LES sensors for pressure-induced separation
    2. Acceleration of transition from RANS to LES (→ „grey area“ mitigation)
    3. Underlying RANS model (→ better representation of separation point)

1. RANS/LES sensors for pressure-induced separation

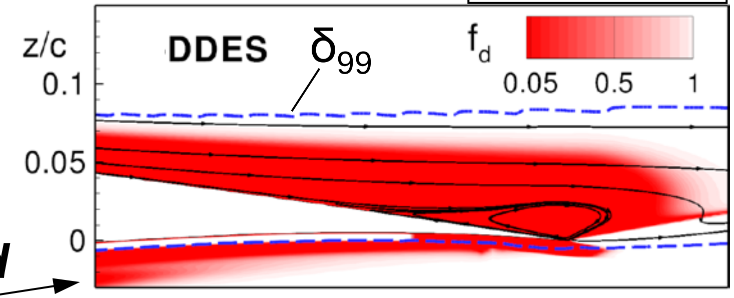
- Shortcomings of DDES
  - No reliable “shielding” of attached BLs
  - No clear RANS/LES interface at separation
- DLR development <u>A</u>lgebraic <u>DDES</u> (**ADDES**)
  - Boundary-layer (BL) detection
  - Separation detection
  - Algebraic RANS/LES sensor

DLR

C²A²S²E

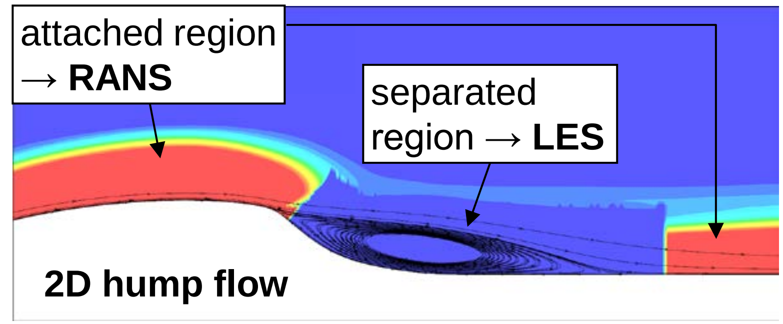
Scale resolving simulations

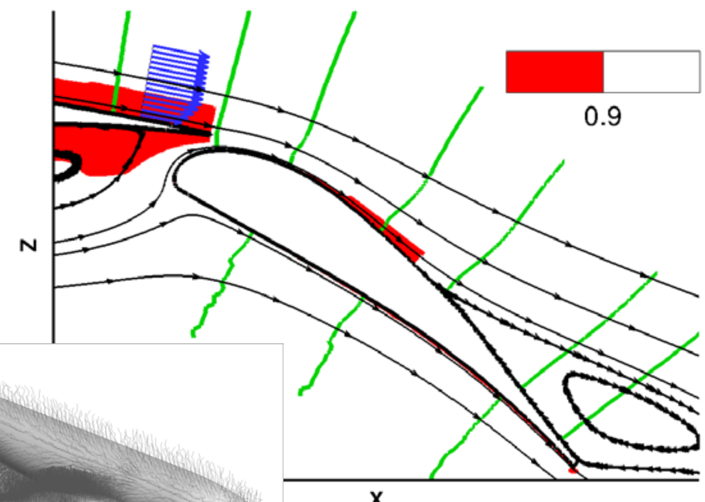
red: RANS
white: LES

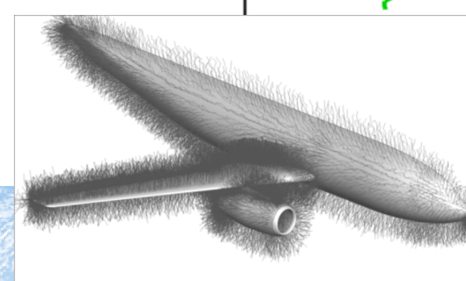


Extended approach

- **Improved Modeling** → ADDES
  1. ***RANS/LES sensors for pressure-induced separation***
     - **BL detection**
       - algebraic BL criteria for U_{edge}
       - search algorithm to detect δ_{99}
     - **Separation detection**
       - Shape factor $H = \delta^* / \Theta \rightarrow H_{crit}$ as separation criterion (Castillo et al., 2004)
     - H_{crit} RANS-model dependent → calibration necessary
     - **Algebraic RANS/LES sensor**
       - RANS mode if: $d_w < \delta_{99}$ and $H < H_{crit}$
       - LES mode if: $H > H_{crit}$



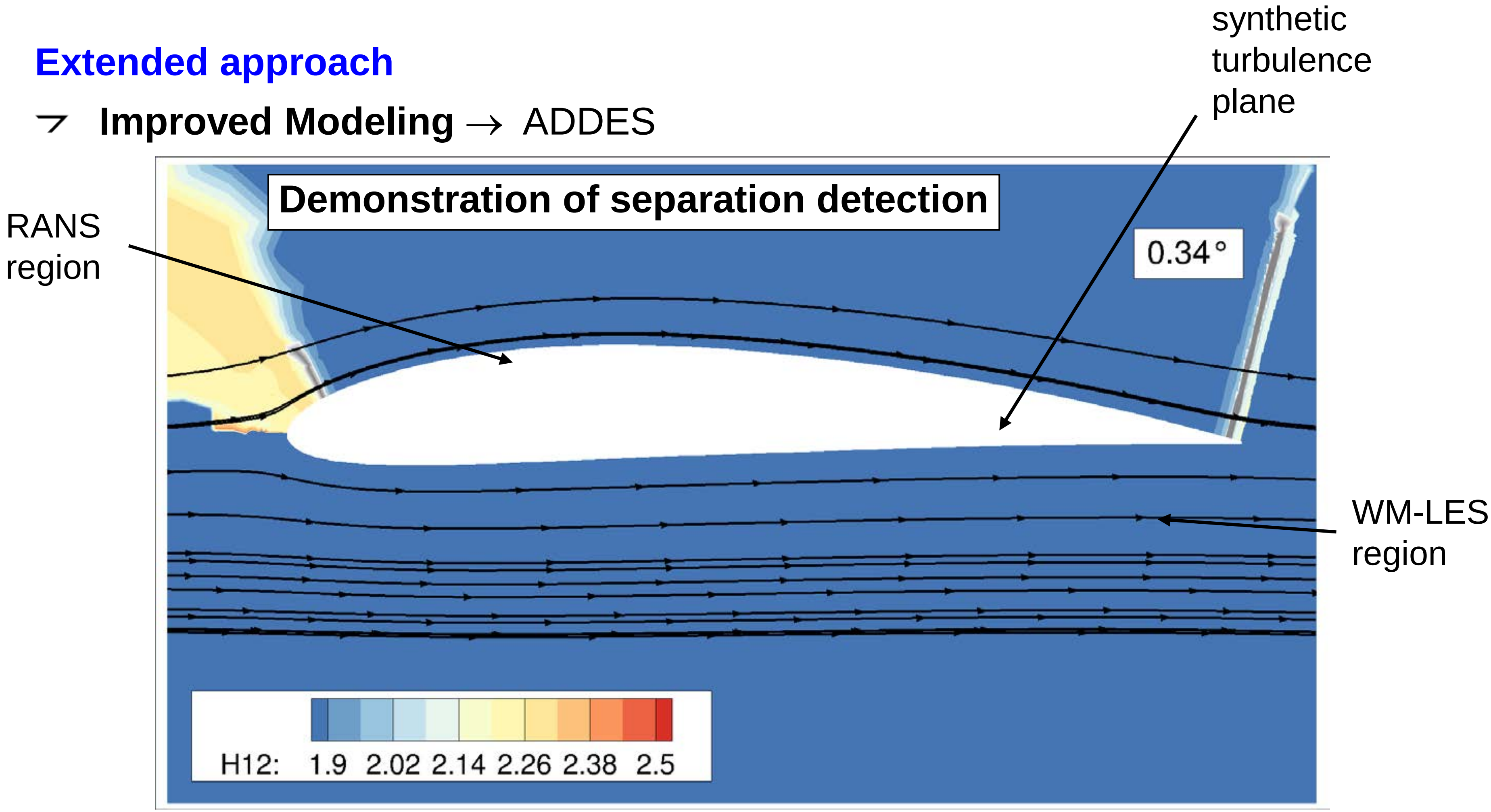




Scale resolving simulations

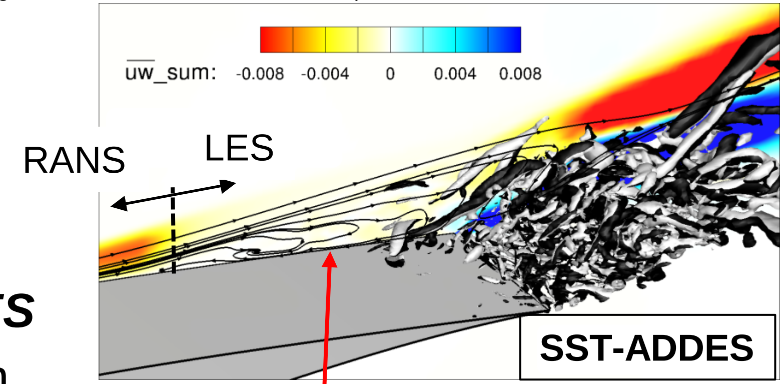
Extended approach

- **Improved Modeling** → ADDES



- Automatic injection of synthetic turbulence under development

Scale resolving simulations



Extended approach

2. Acceleration of transition from RANS to LES

- Hybrid RANS/LES of incipient separation suffers from **"grey area"**:
  - Weak separations rather stable w.r.t. outer disturbances
  - Hybrid RANS/LES switches to LES mode, but **resolved turbulence is delayed**
- **Undefined modelling state** with low total (modelled + resolved) turbulent stress

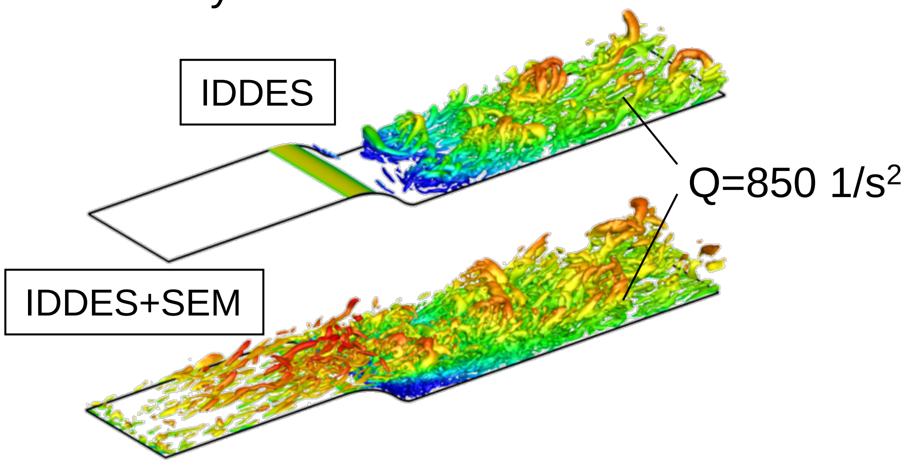
- Techniques for grey area mitigation considered in TAU code:
  1. **Stochastic forcing** of modeled turbulence
  2. Modified **LES scale** considering **local vorticity** vector
     - Both 1. and 2. applicable to rather unstable separation or free shear flow
  3. **Synthetic turbulence** generated from RANS data
     - Complex approach, but applicable to weakly separated or attached flow

Scale resolving simulations

Extended approach

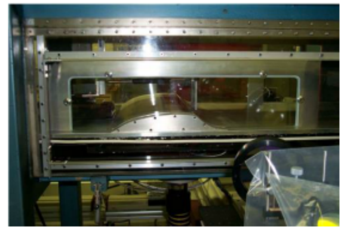
- **Improved Modeling** → Synthetic turbulence (RANS → LES)
  - ***2. Acceleration of transition from RANS to LES***
    - Initial implementation of **Synthetic Eddy Method** (SEM, 2006)
      - Artificial fluctuations generated from given turbulence statistics
      - First tests with SEM applied at inflow boundary:
        - 2D channel flow
        - Rounded step with separation:

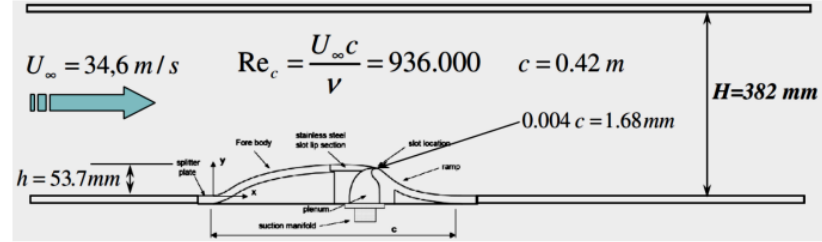
Method	$x_{separation}$	$x_{reattachment}$
IDDES	1.15	6.04
IDDES + SEM	0.72	4.99
LES (reference)	0.83	4.36



- ***Ongoing:***
  - Full integration in hybrid RANS/LES (i.e. combination with ADDES)

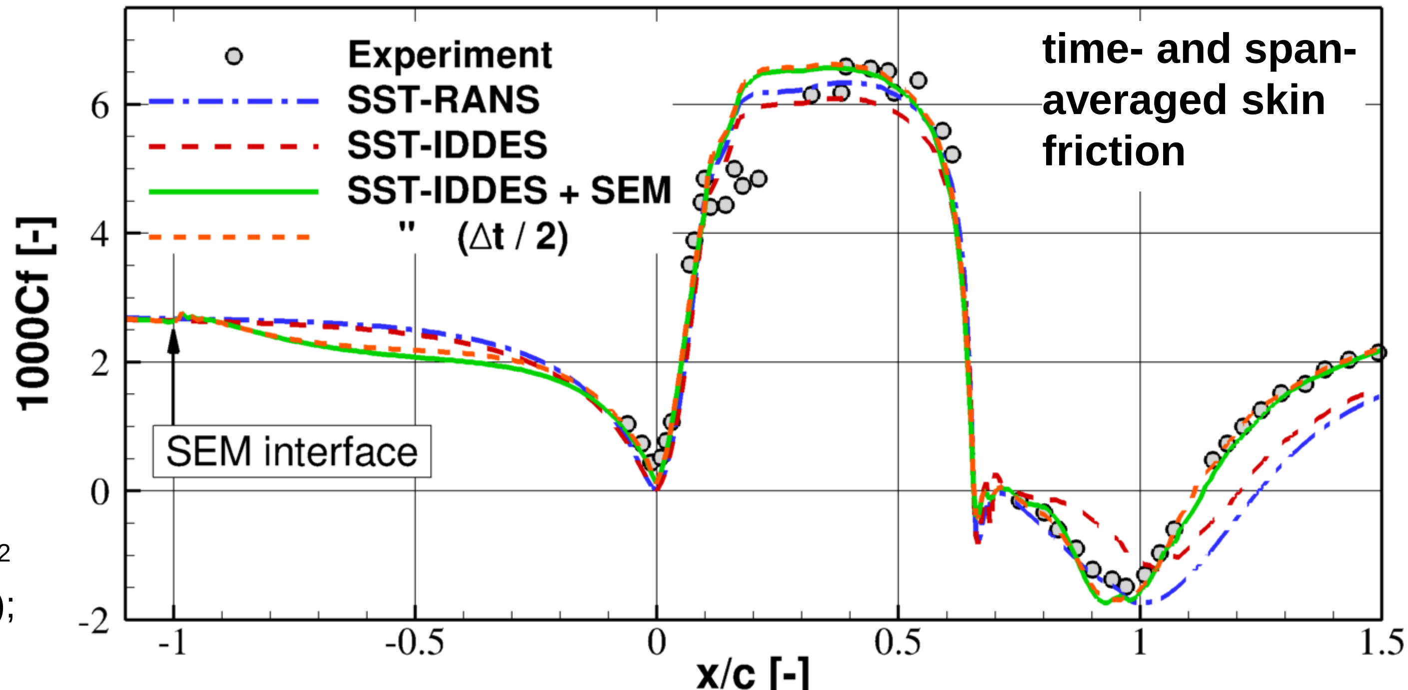
Scale resolving simul



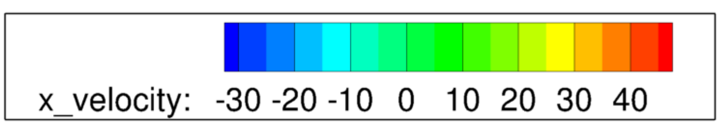


Extended approach

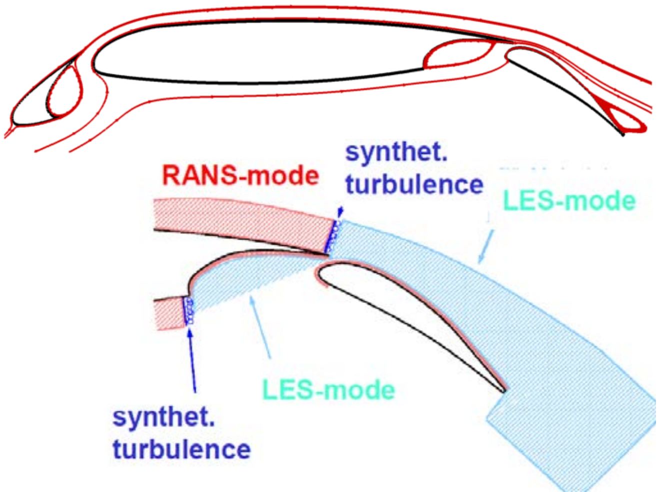
- **Improved Modeling** → Synthetic turbulence (RANS → LES)
  - 2D wall-mounted hump



Snapshot of: $\lambda_2 = 5 \cdot (U/c)^2$ (SST-IDDES + SEM(x=-1); mand. time step)



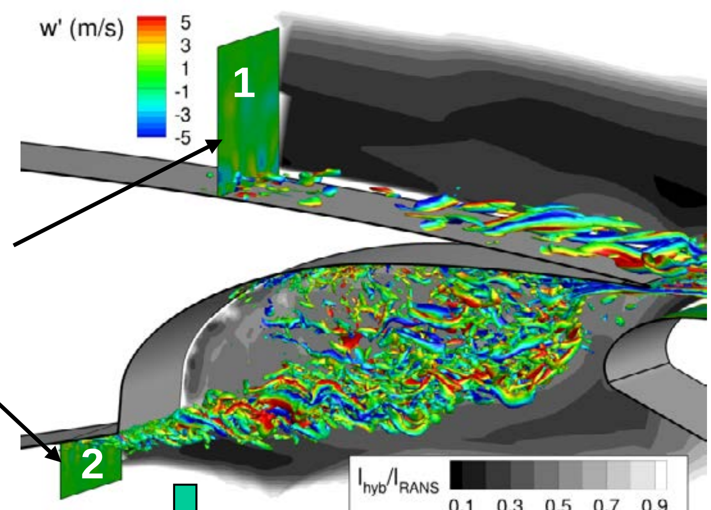
Scale resolving simulations

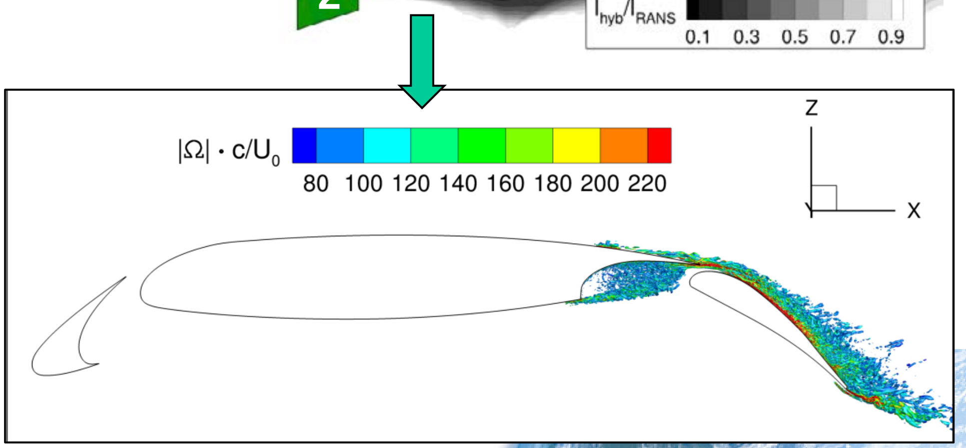


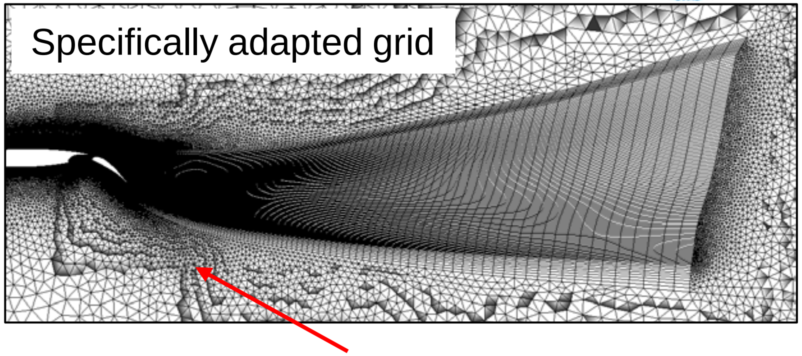
Extended approach

- **Improved Modeling** → Synthetic turbulence
  - DLR-F15 at **Re = 2×10⁶** and **α = 6**

Snaphots:







- **Embedded WM-LES:**
1) Restricted to flap region
2) SEM at interfaces
3) Large grid-point savings possible:
   - high-resolution structured grid in LES region (flap + wake)
   - coarser unstructured outer part → **-62%** grid points (baseline grid: 27 mio. points)

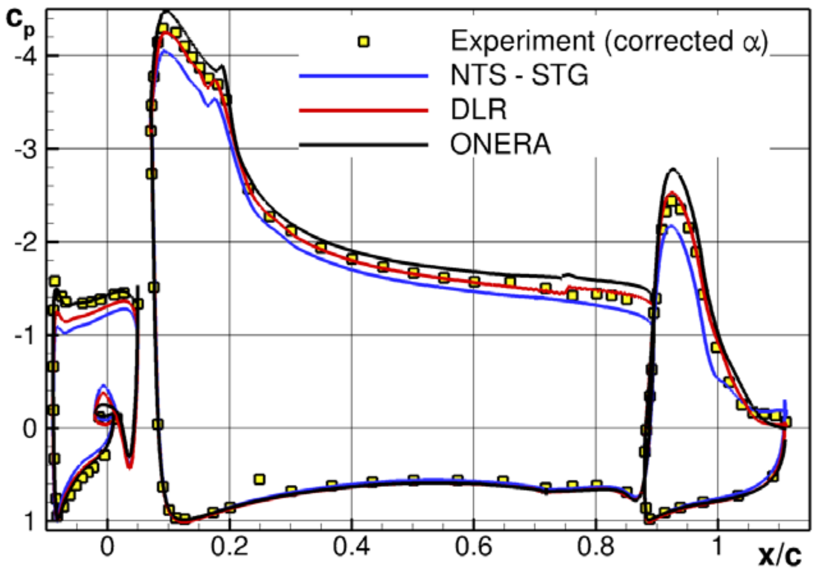
Scale resolving simulations

Extended approach

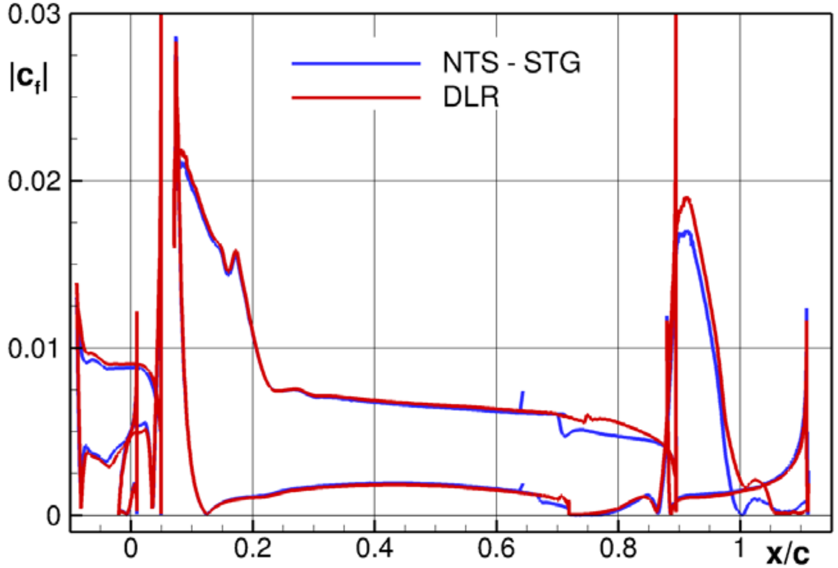
- **Improved Modeling** → Synthetic turbulence
  - DLR-F15 at **Re = 2×10⁶** and **α = 6**

Cross-comparison with project partners from EU project Go4Hybrid

Mean surface pressure:

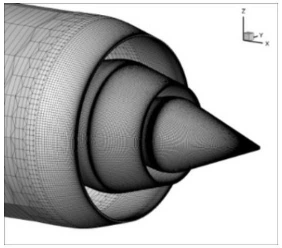


Mean skin friction:



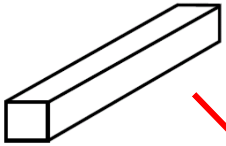
➢ reasonable agreement between different „zonal“ approaches

Scale resolving simulations



Extended approach

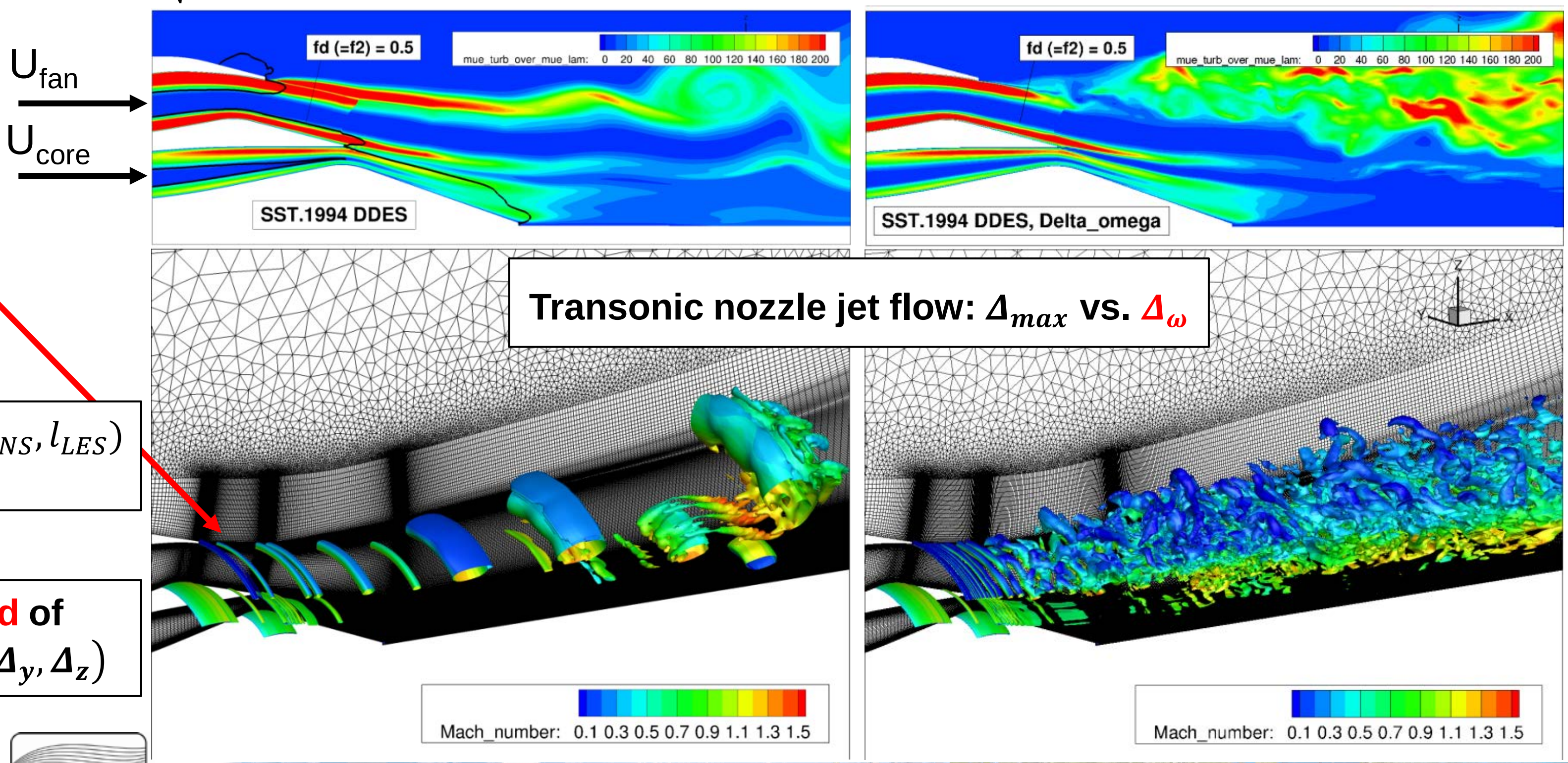
- **Improved Modeling** $\rightarrow$ **Modified LES scale** using local vorticity vector ($\vec{N}$)
  - Transition from RANS to LES: Take into account local orientation of vortices
  - $\Delta_\omega = \sqrt{N_x^2 \Delta_{y,max}\Delta_{z,max} + N_y^2 \Delta_{x,max}\Delta_{z,max} + N_z^2 \Delta_{x,max}\Delta_{y,max}}$



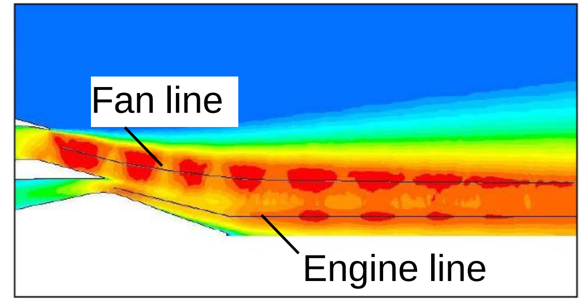
(c) pencil-shaped cell

$l_{DDES} = f_{DDES}\,(l_{RANS}, l_{LES})$
with $l_{LES} = C \cdot \Delta_\omega$

Use Δ_ω instead of $\Delta_{max} = max(\Delta_x, \Delta_y, \Delta_z)$



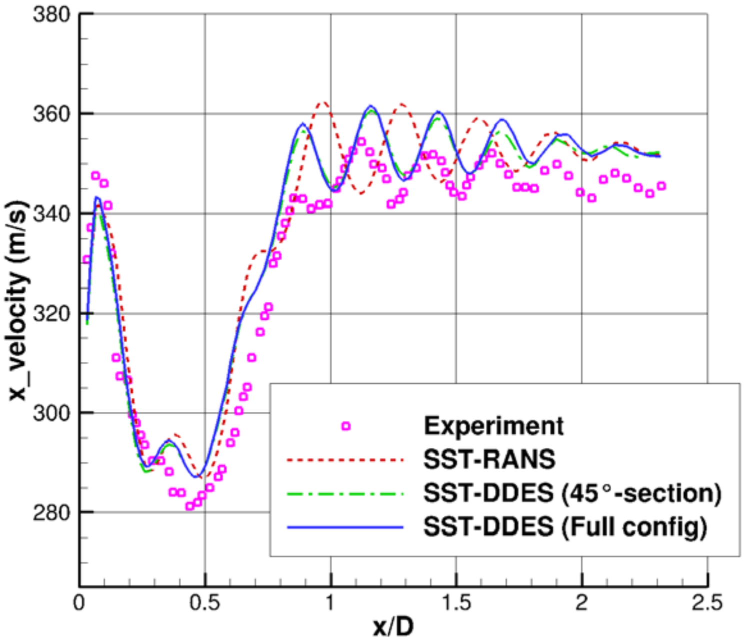
Scale resolving simulations



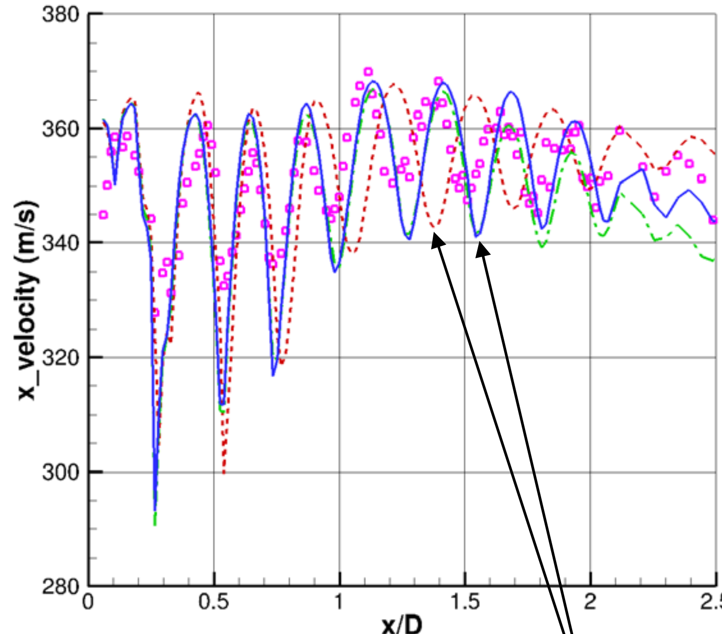
Extended approach

➝ **Improved Modeling → Modified LES scale**

Engine line:



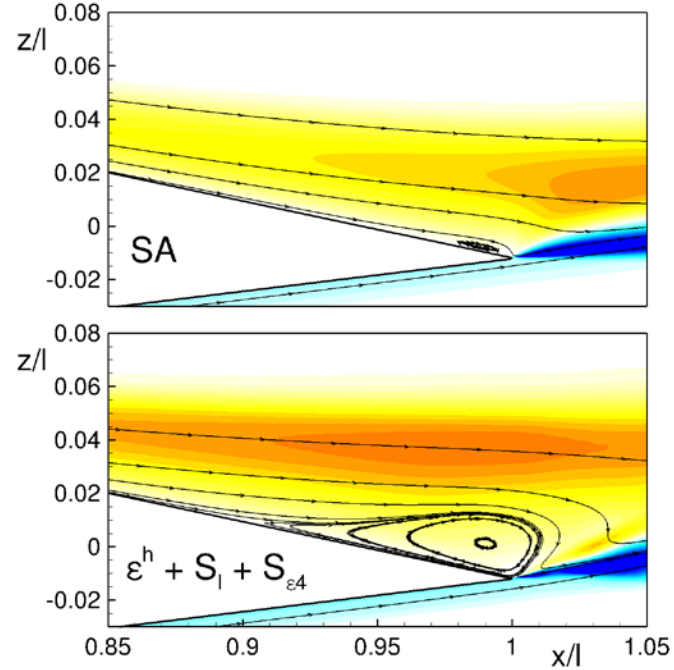
Fan line:



- axial oscillations (Ma-cells) captured by all simulations
- „wave length“ better predicted by HRLM (increasing phase shift with RANS)

Quelle: Diss. A. Probst

Scale resolving simulations



Extended approach

3. *Underlying RANS model*

- RANS model **determines inflow boundary and location of LES region**
- DDES solution sensitivity w.r.t. RANS model
  - ***Low*** for flows with ***massive separation***, e.g. airfoils at deep stall, step flows, …
  - ***Large*** for more ***practical flows***, e.g. airfoil near stall, distorted intake flow, …
  - **Example:** ONERA-A airfoil at maximum lift (Re = 2 Mio.)

	x_{sep}/l
Experiment	**0,83**
SA	0,96
SSG/LRR RSM	**0,89**
ε^h-RSM	**0,88**

- DDES at flight boundaries requires more advanced RANS models, i.e. **Reynolds-stress models** (RSM)

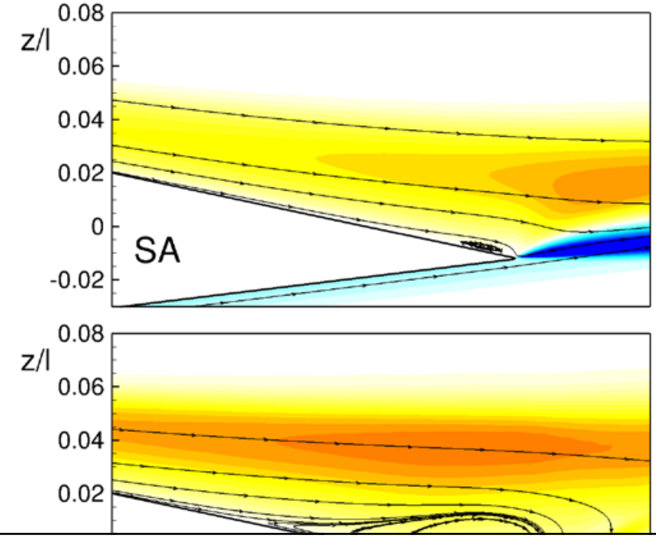
Scale resolving simulations

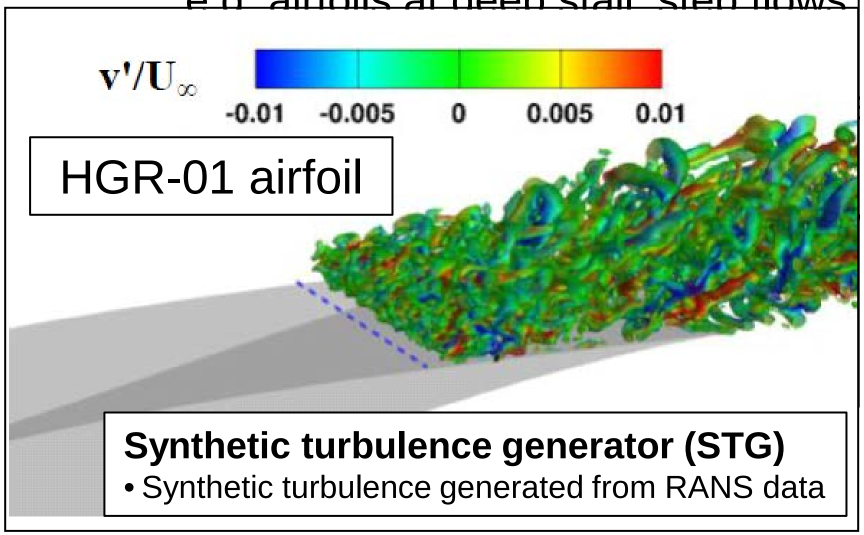
Extended approach

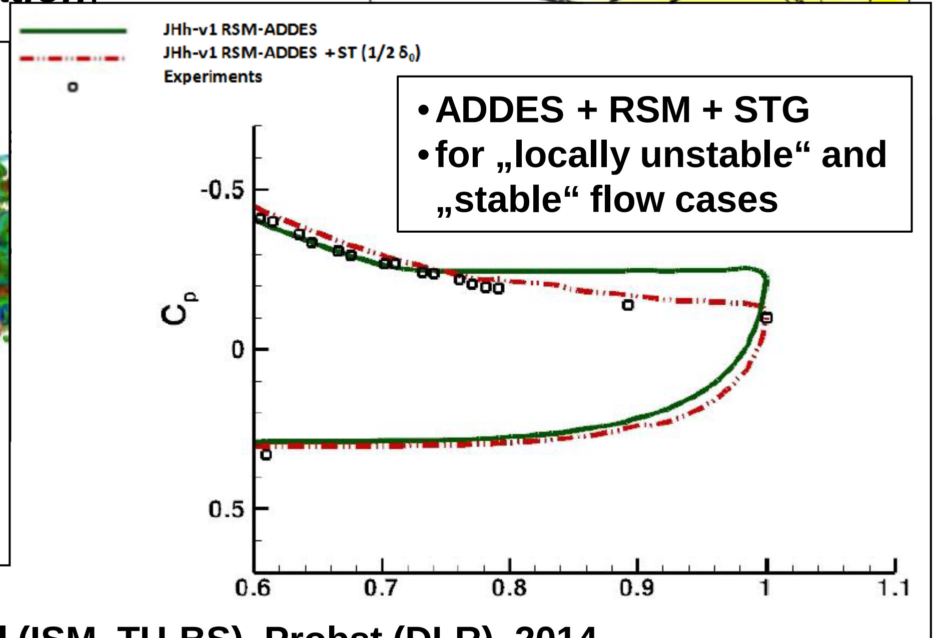
3. *Underlying RANS model*

- RANS model **determines inflow boundary and location of LES region**
- DDES solution sensitivity w.r.t. RANS model
  - ***Low*** for flows with ***massive separation***, e.g. airfoils at deep stall, step flows

Quelle: Diss. A. Probst



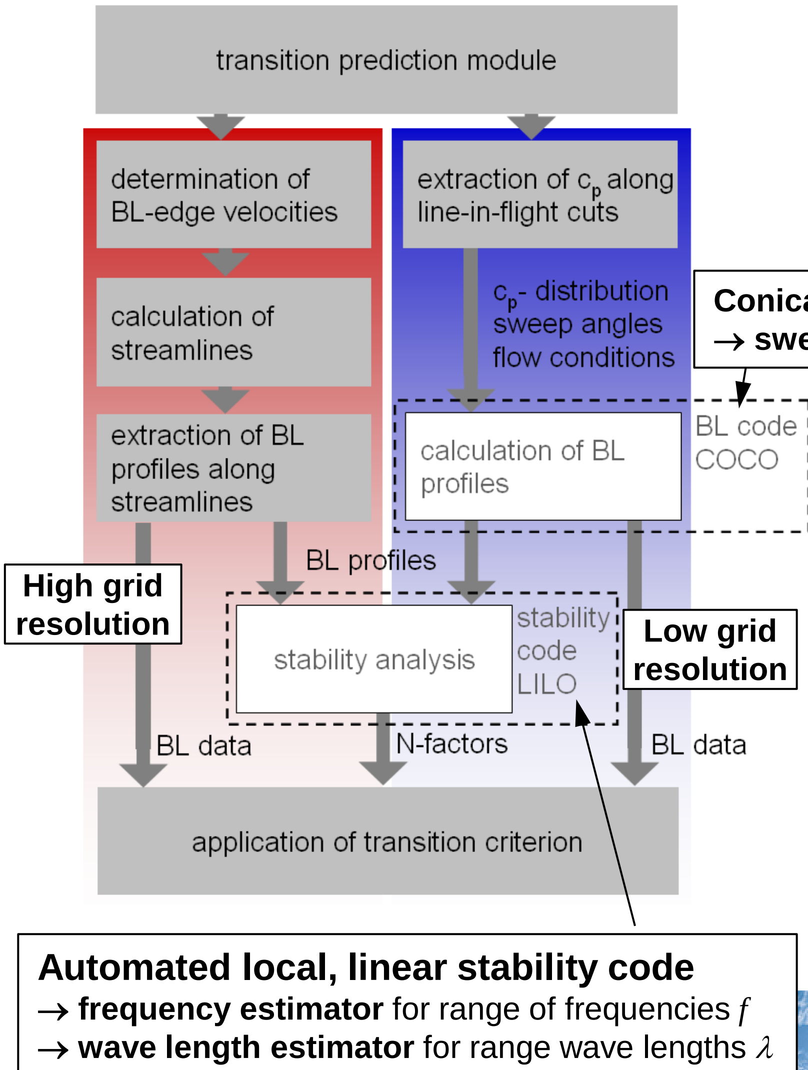




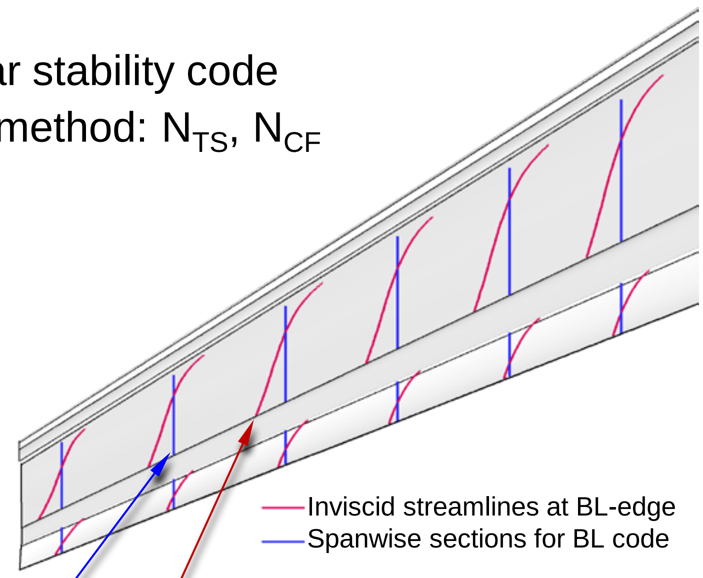
François, Radespiel (ISM, TU-BS), Probst (DLR), 2014

Transition Prediction and Modeling

Transition Prediction Module



- **e^N method**
  - Local, linear stability code
  - 2-N-factor-method: N_{TS}, N_{CF}



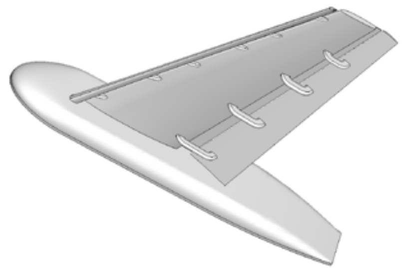
- ***Line-in-flight* cuts**
  → swept tapered wings
- **Inviscid streamlines**
  - Necessary for fuselages, nacelles etc.
  - Start at attachment line
- **Execution of the stability code along these lines**
  - One single transition point per cut/line.
  - Transition line is a polygonal line on the surface.

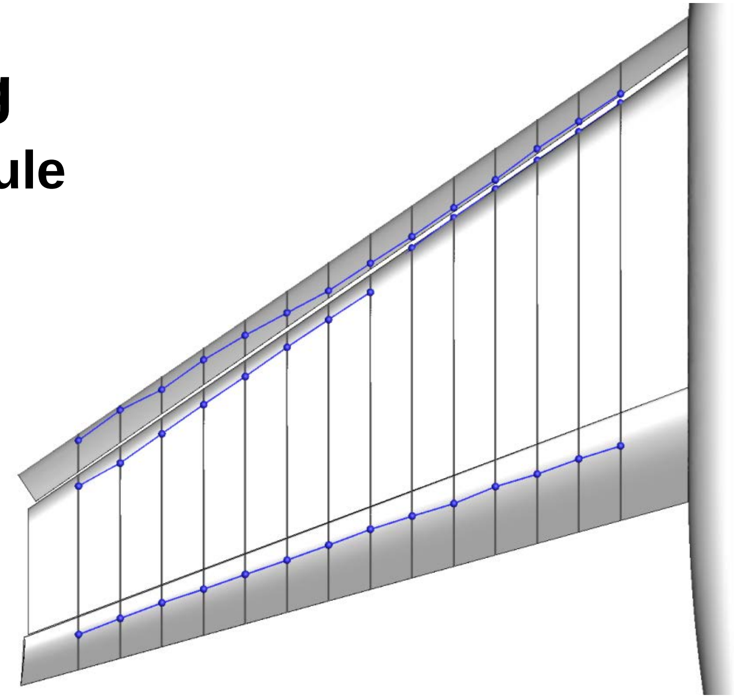
Transition Prediction and Modeling

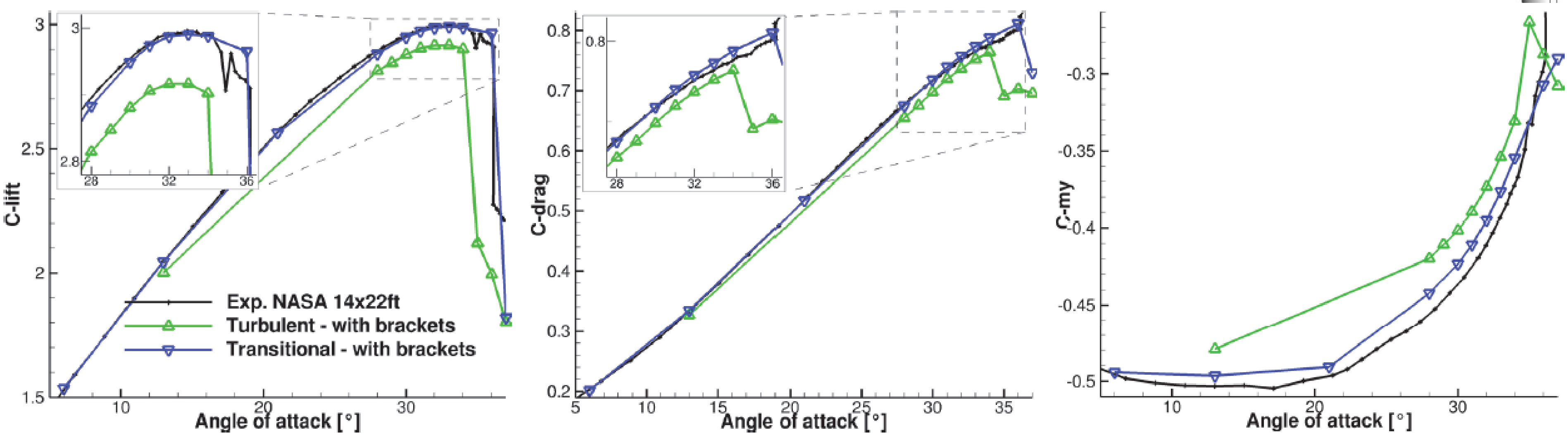
Application of Transition Prediction Module

NASA trapezoidal wing, 1st HiLiPW

- M = 0.2, Re = 4.3×10^6, $\alpha = 6° - 36°$
- $N_{TS} = 8.5$, $N_{CF} = 8.5$





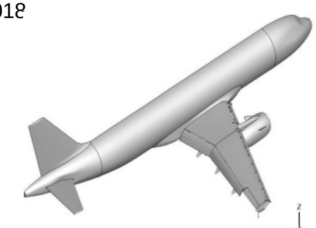


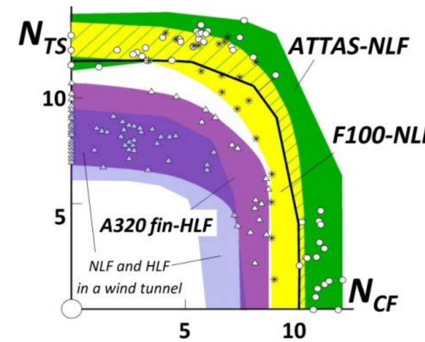
DLR

C²A²S²E

Transition Prediction and Modeling

Application of Transition Prediction Module

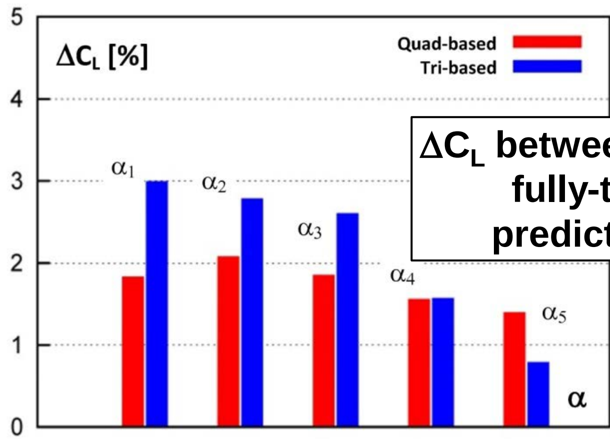




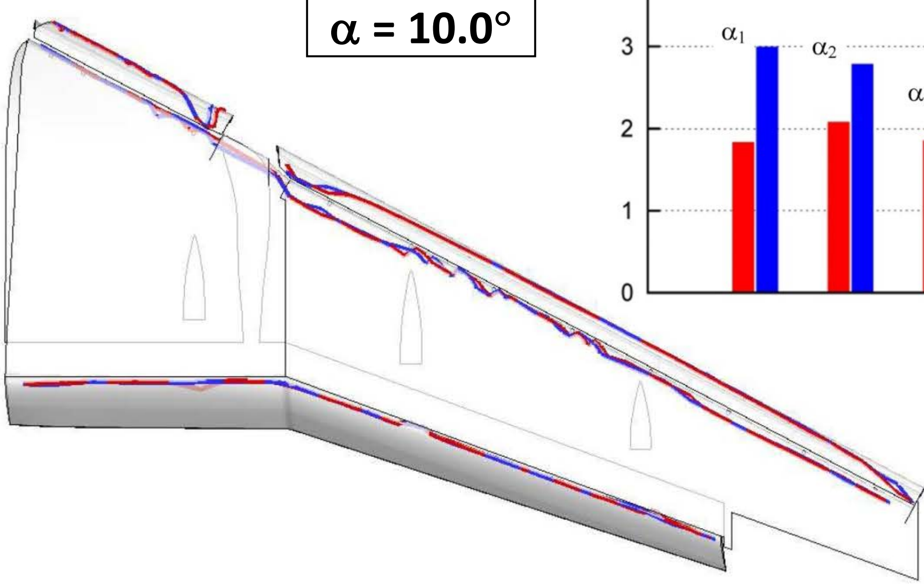
DLR A320 D-ATRA high-lift landing configuration

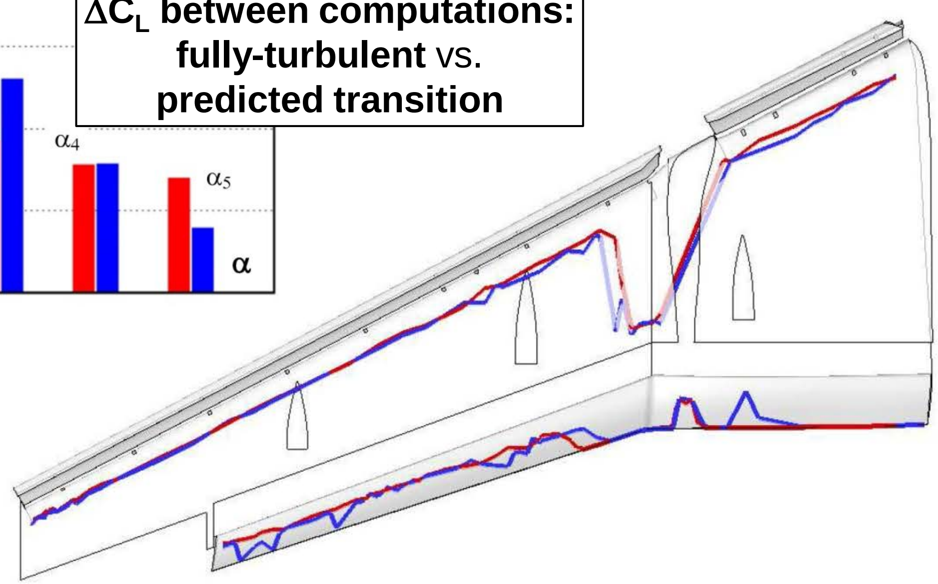
- M = 0.2, Re = 17×10^6
- Two different grids

α = 10.0°



ΔC$_L$ between computations:
fully-turbulent vs.
predicted transition





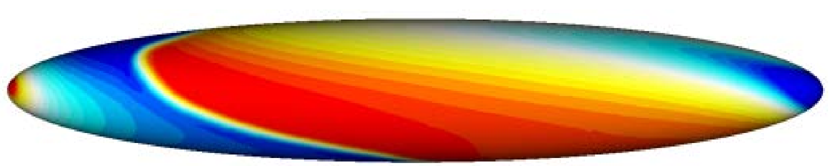
Suction side **Pressure side**

Transition Prediction and Modeling

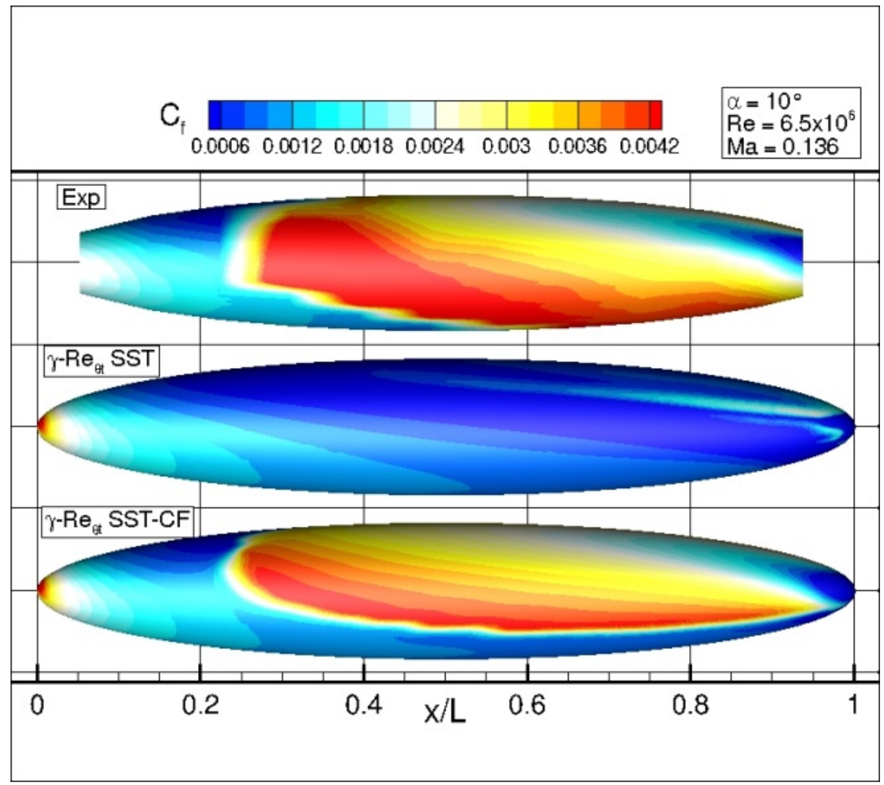
Transport equation model – γ-$Re_{\theta t}$ model

- Basic model covers TS-, bypass- and separation induced transition
- ***DLR development:*** CF-extension of the basic model → **γ-$Re_{\theta t}$-CF model**
- Coupled to Menter SST k-ω and SSG/LRR-ω/g turbulence models

- **Validation**
  - Inclined prolate 6:1 spheroid
  - Re = 6.5x10^6, Ma = 0.13, α = 10.0°
  - Mixed T-S/CF transition



Two-N-factor strategy

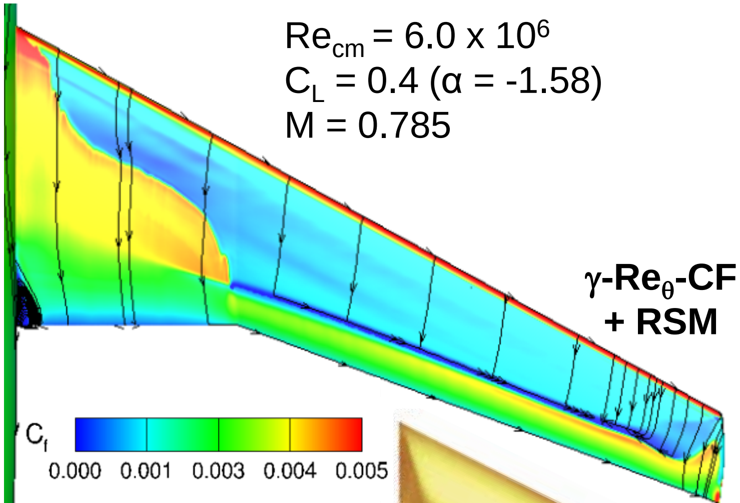


Transition Prediction and Modeling

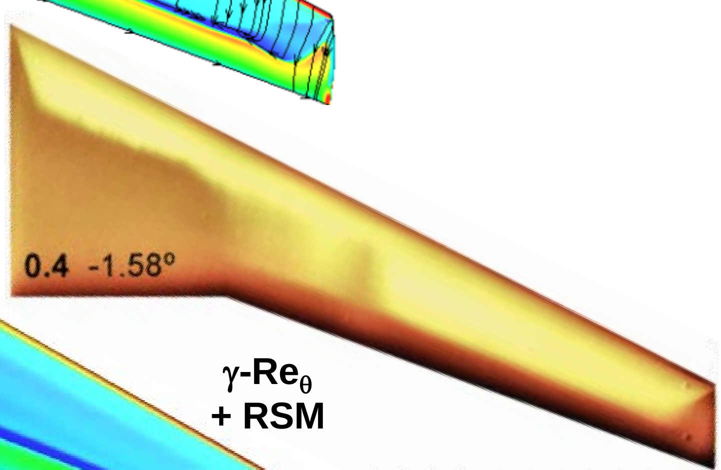
Application of Transition Equation Model

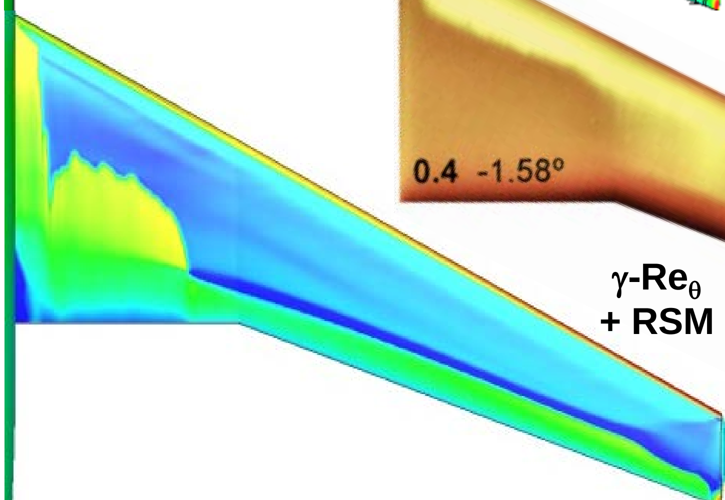
DLR-F4 Wing-Body

$Re_{cm} = 6.0 \times 10^6$
$C_L = 0.4$ ($\alpha = -1.58$)
$M = 0.785$



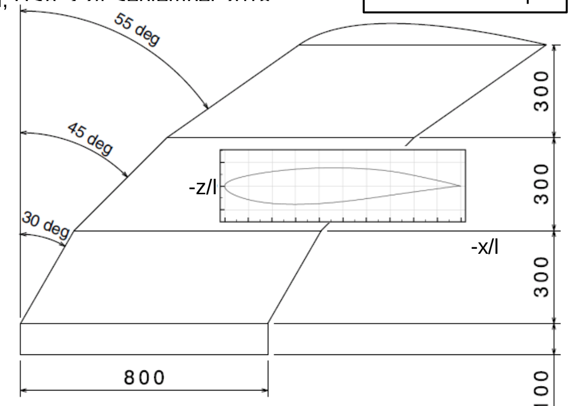
γ-Re_θ-CF + RSM

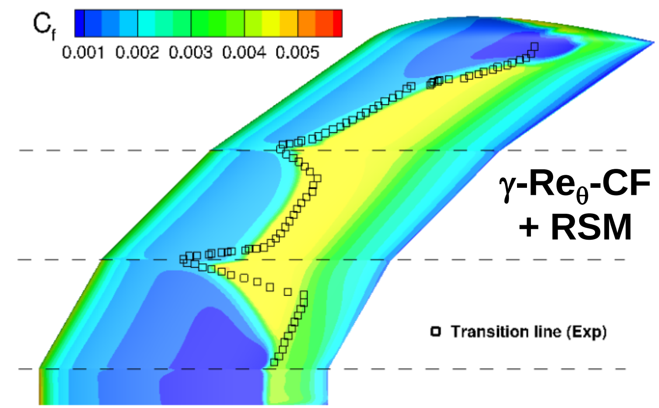




γ-Re_θ + RSM

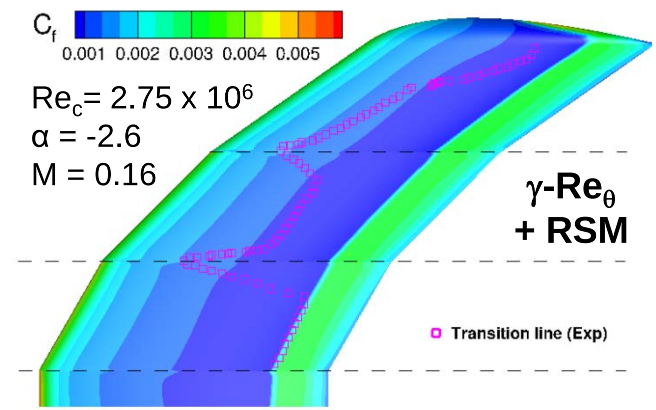
Petzold & Radespiel





γ-Re_θ-CF + RSM

$Re_c = 2.75 \times 10^6$
$\alpha = -2.6$
$M = 0.16$



γ-Re_θ + RSM

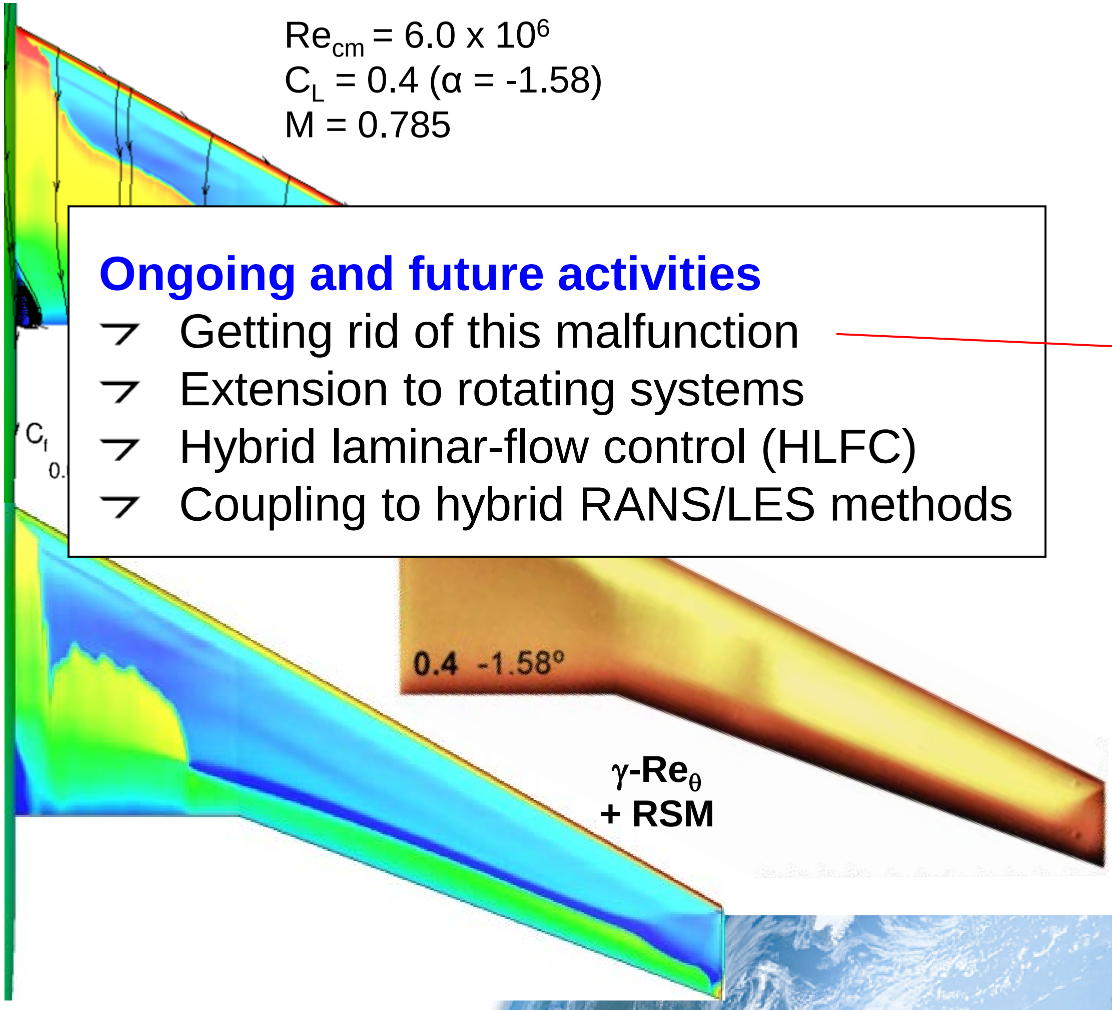
TU Braunschweig Sickle Wing

Transition Prediction and Modeling

Application of Transition Equation Model

DLR-F4 Wing-Body

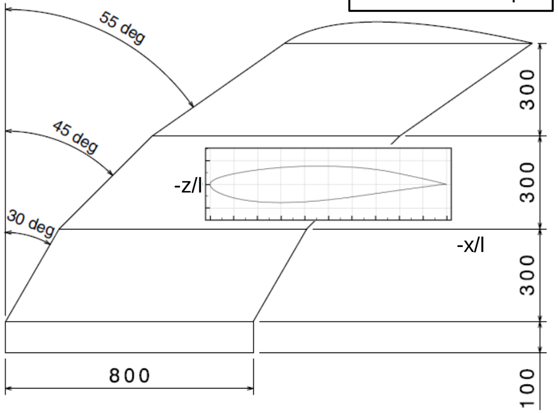
$Re_{cm} = 6.0 \times 10^6$
$C_L = 0.4$ ($\alpha = -1.58$)
$M = 0.785$

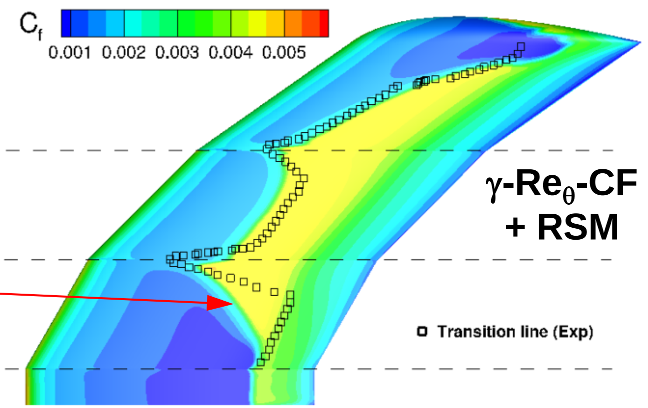


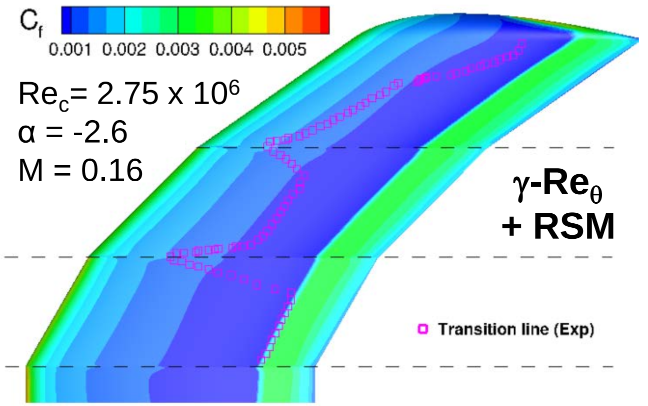
Ongoing and future activities

- Getting rid of this malfunction
- Extension to rotating systems
- Hybrid laminar-flow control (HLFC)
- Coupling to hybrid RANS/LES methods

Petzold & Radespiel







TU Braunschweig Sickle Wing

Turbulence modeling improvements

Challenge: Separated flow

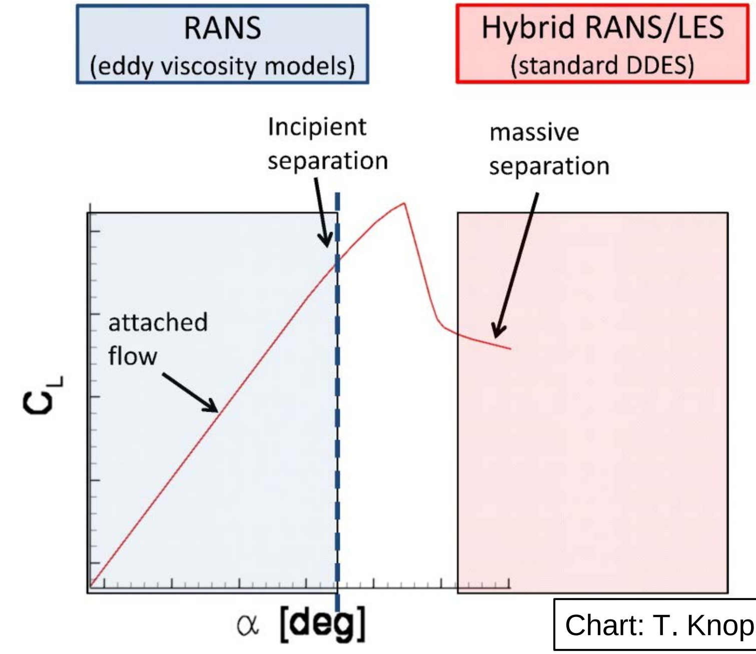


Chart: T. Knopp

Technology gap for **moderate separation**
- Maximum lift
- Shock induced separation

Need for better RANS turbulence models

- Today, simulation of *moderately separated* flows **not reliable**, neither with RANS, nor with hybrid RANS/LES methods (HRLM).
- RANS models needed for next decades
  - Due enormous computational costs for LES
  - Pure RANS → highly complex configurations
  - HRLM → components of aircraft or special configurations (fighter)
- Technology gap **must be closed**
  - Insignificant unsteadyness → RANS
  - Significant unsteadyness → hybrid RANS/LES
- Identification of significant physical phenomena necessary
  - Flow separation, boundary-layer representation, shock/BL interaction
  - Transition
  - Wake modeling, vortical flows
  - Engine jet flows, …

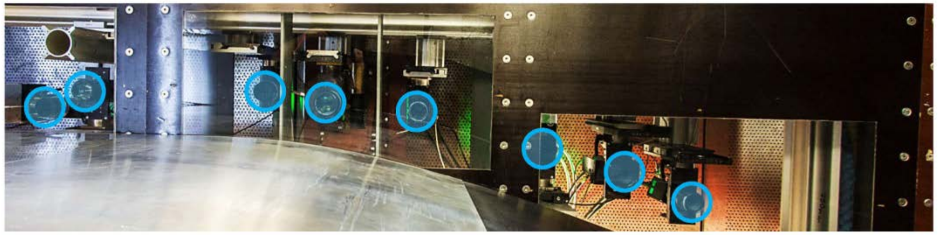
⇒ Dedicated RANS turbulence modeling improvements for specific flow phenomena

Turbulence modeling improvements

Change of current turbulence modeling paradigm

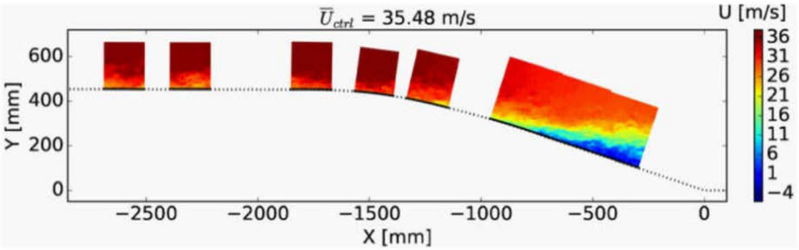
- Focus **not** on validation of existing models using experiments
- **Instead:** use experiments to derive specific model modifications
- Twofold approach
  - **Identify** significant physical **quantities and laws** for specific identified phenomena
  - Derive models satisfying identified laws
- **Design of experiments** for phenomenon specific flows of major relevance
  - Dedicated physical experiments in wind tunnel
  - Numerical experiments using LES/DNS
- Finally, go back to traditional validation using more complex cases.

VicToria experiment
$\rightarrow$ toward flight Re_θ=35,000 in APG region

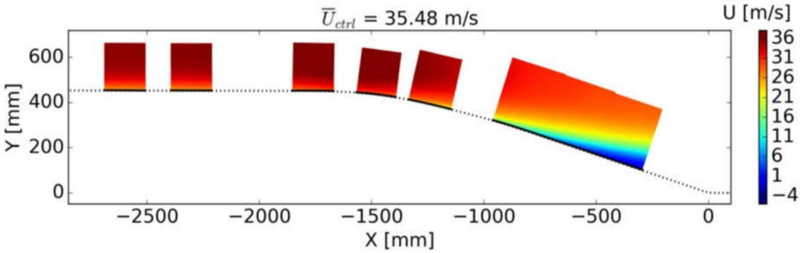


Large-scale overview measurement: 2D-2C PIV

Instantaneous snapshot



Statistically averaged flow field



Turbulence modeling improvements

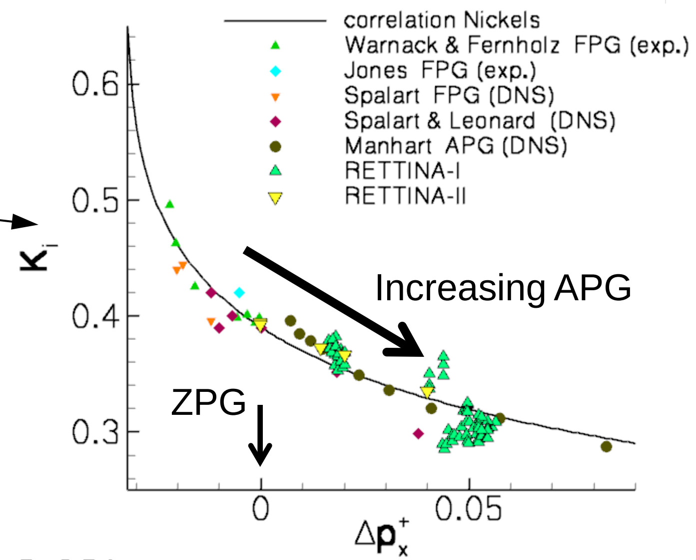
Reduction of „Karman constant“ with increasing adverse pressure gradient

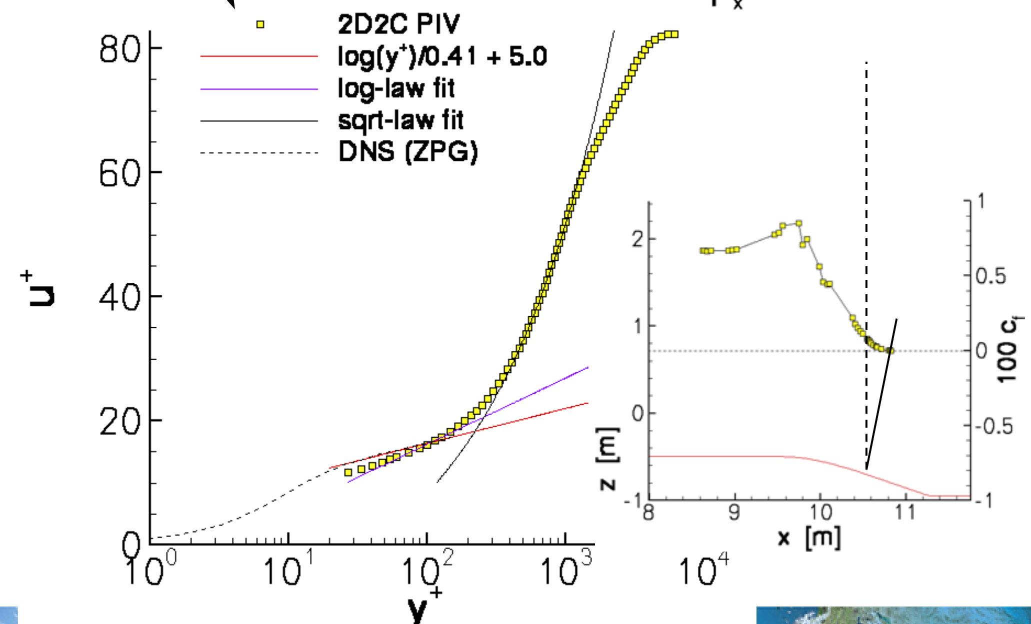
Ongoing: Improvement for incipient separation

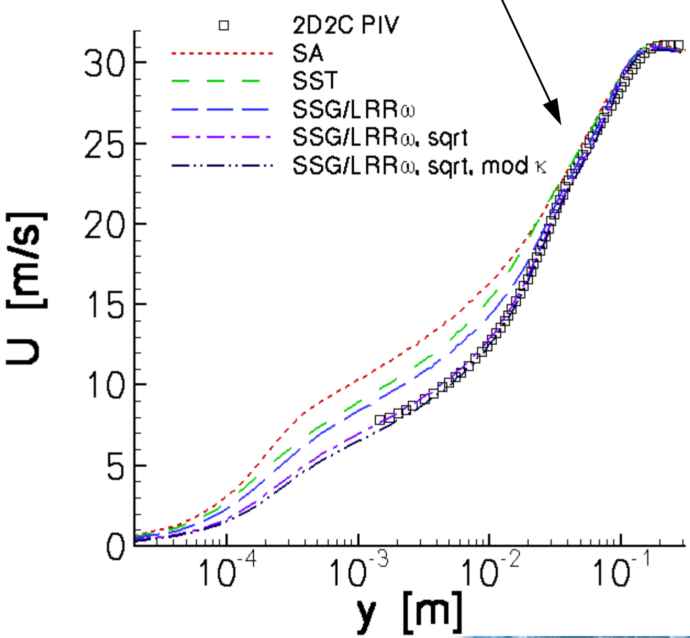
Step I: Establish a high-quality data base from experiments & DNS

Step II: Find law-of-the-wall for mean velocity and Reynolds stresses at dp/dx > 0

Step III: Use new wall-laws to improve RANS models







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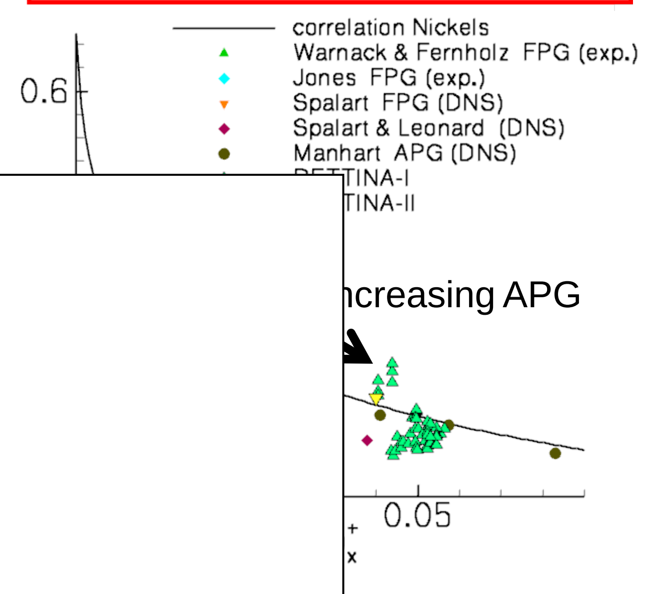
Reduction of „Karman constant“ with increasing adverse pressure gradient



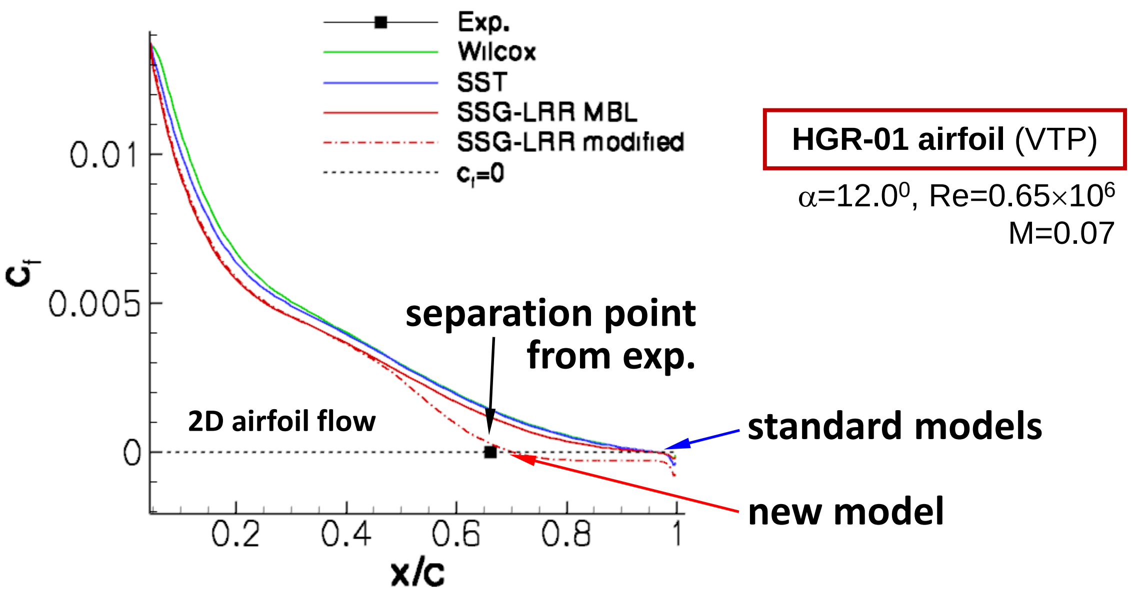
Ongoing: Improvement for incipient separation

Step I:

Step II:

Step III:

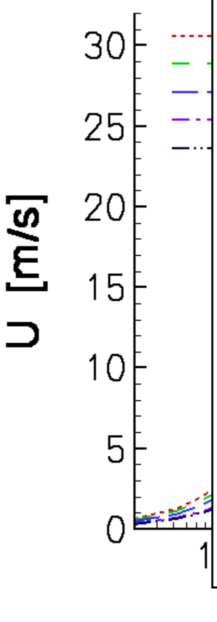
A very first step towards validation:

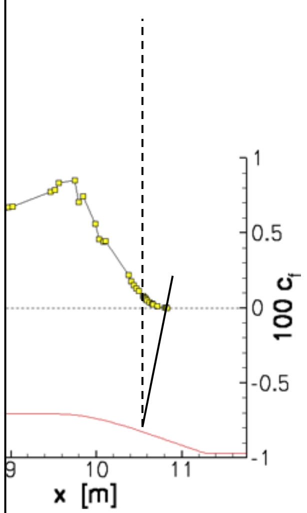


HGR-01 airfoil (VTP)

α=12.0⁰, Re=0.65×10⁶

M=0.07





Turbulence modeling improvements

Further modeling activities

- ***Improvements for general shear layer flows***
  - Based on experimental data from literature
  - Different data sets defining the **anisotropy** of the **Reynolds shear-stresses**
  - **Boundary layer, plane jet, axisymmetric jet, plane mixing layer**
  - Resolves the round-jet/plane-jet anomaly
    $\rightarrow$ both correct using the corresponding data set
  - Theory ready, implementation ongoing
- ***Improvements for turbulent wake under APG***
  - Collaboration with Braunschweig University and NTS (St. Petersburg, Russia)
  - Braunschweig University carries out experiment
  - NTS does IDDES for the exp. test case
  - Recently started
- ***Data-driven approaches for model augmentation***
  - Planned to start next year

Challenge: Separated flow

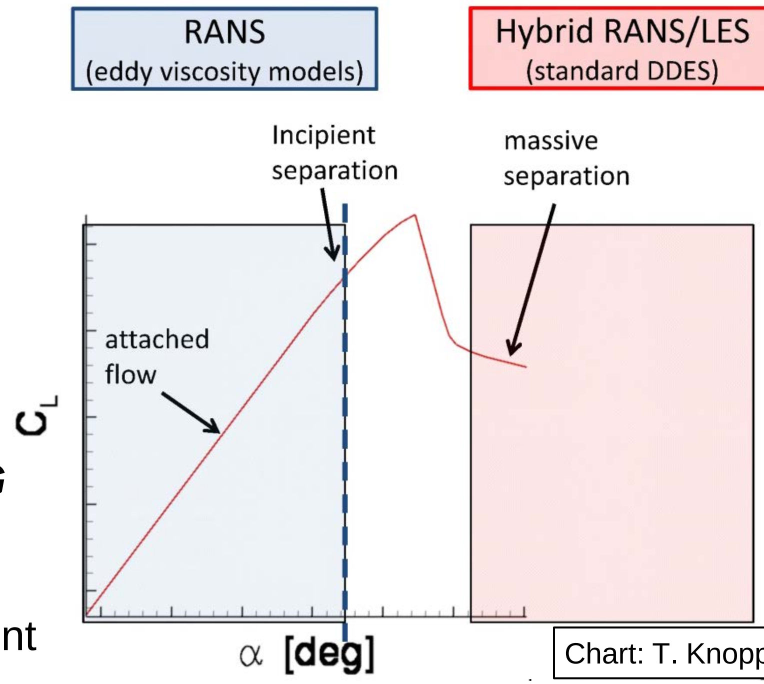


Chart: T. Knopp

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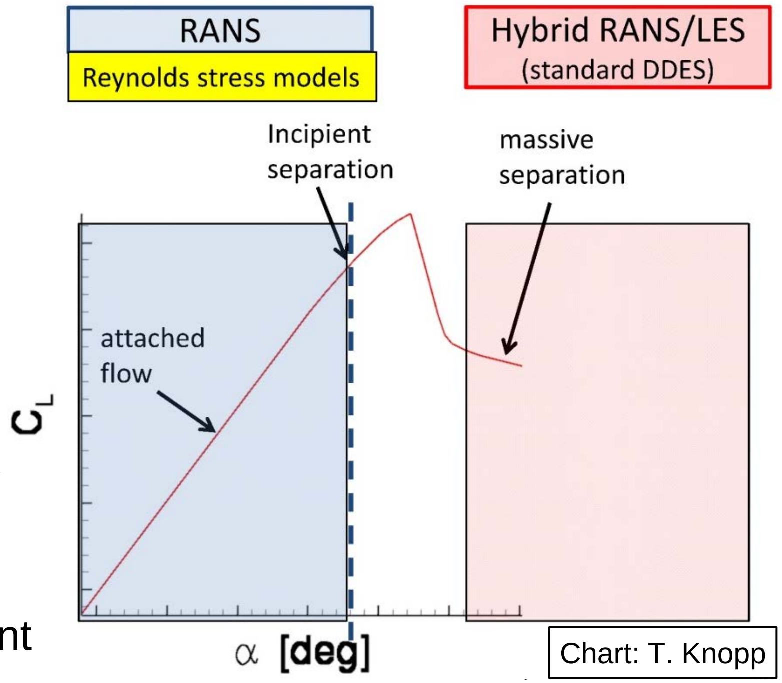

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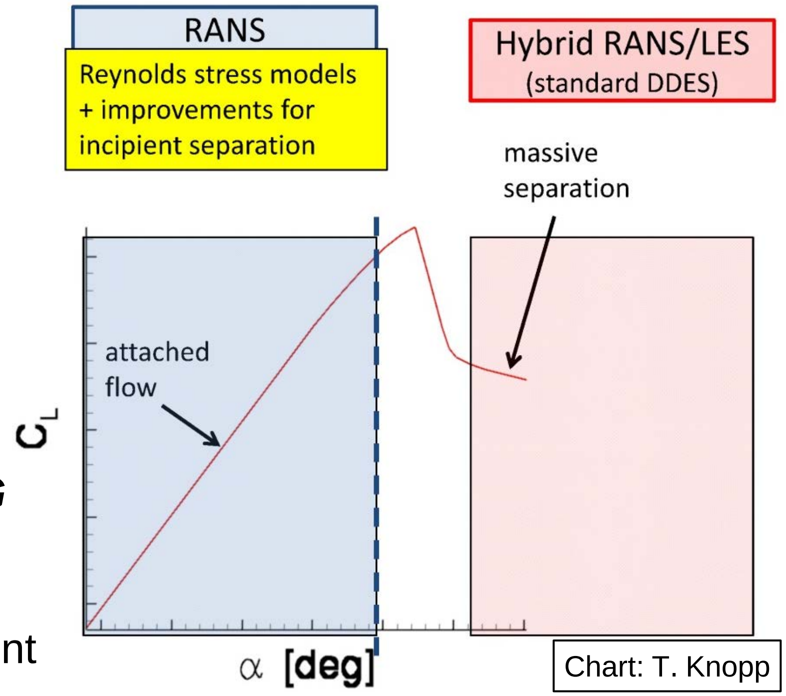

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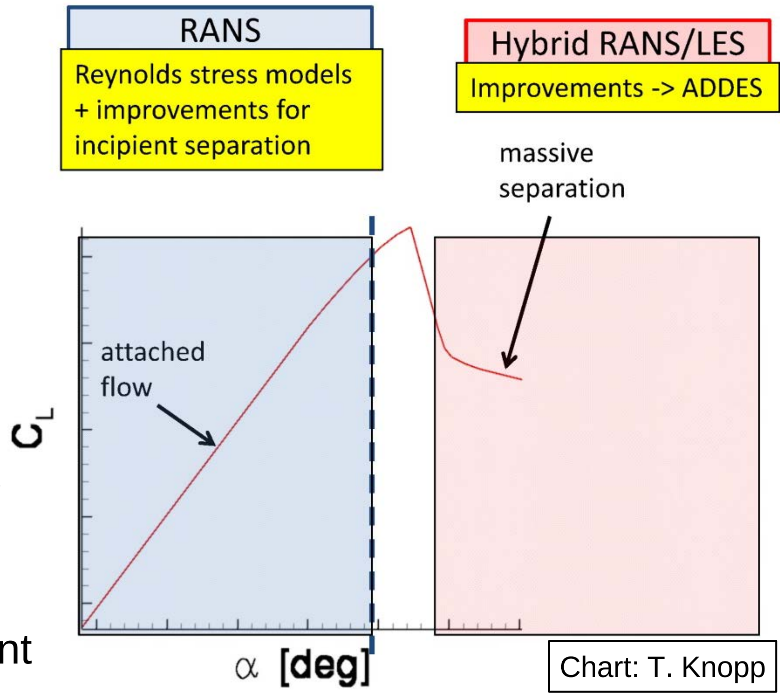

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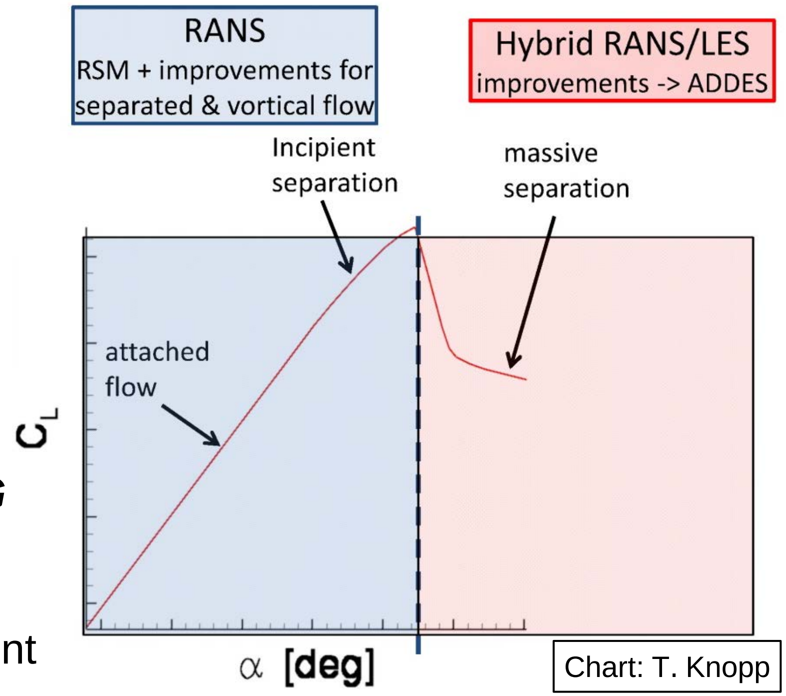

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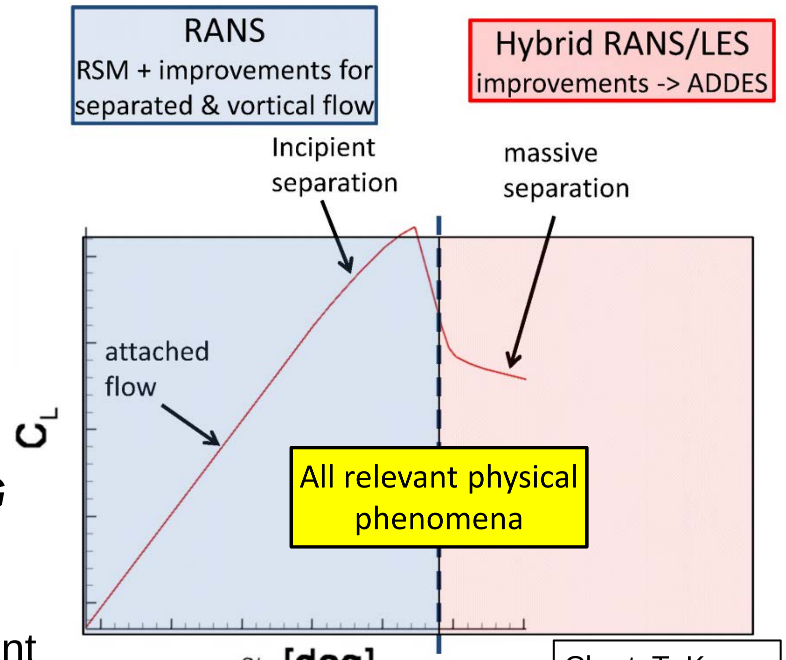

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